Accident Scenario Analysis for Maritime Operations

by

Md. Al-Amin Baksh, MSc (Computational Science), BSc (Statistics)

National Centre for Maritime Engineering and Hydrodynamics
Australian Maritime College

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University of Tasmania

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Md. Al-Amin Baksh

Statement of Co-Authorship

The following people and institutions contributed to the publication of work undertaken as part of this thesis:

Md. Al-Amin Baksh, Australian Maritime College

Prof Faisal Khan, Primary Supervisor, Australian Maritime College

Dr Vikram Garaniya, Co-Supervisor, Australian Maritime College

Dr Rouzbeh Abbassi, Co-Supervisor, Australian Maritime College

Paper 1 (Chapter 2): ***A Network Based Approach to Envisage Potential Accidents in Offshore Process Facilities.***

Al-Amin Baksh was the primary author and with Faisal Khan, Vikram Garaniya, and Rouzbeh Abbassi contributed to the conception and design of the research project and drafted significant parts of the paper.

Percentage of Contribution: *Candidate 70%, Faisal Khan 12%, Vikram Garaniya 8%, Rouzbeh Abbassi 10%.*

Paper 2 (Chapter 3): ***Marine Transportation Risk Assessment Using Bayesian Network: Application to Arctic Waters.***

Al-Amin Baksh was the primary author and with Faisal Khan, Vikram Garaniya, and Rouzbeh Abbassi contributed to the conception and design of the research project and drafted significant parts of the paper.

Percentage of Contribution: *Candidate 70%, Faisal Khan 10%, Vikram Garaniya 8%, Rouzbeh Abbassi 12%.*

Paper 3 (Chapter 4): ***Dynamic Risk Model for Marine Vessel Collision Avoidance in Narrow Channel.***

Al-Amin Baksh was the primary author and with Faisal Khan, Vikram Garaniya, and Rouzbeh Abbassi contributed to the conception and design of the research project and drafted significant parts of the paper.

Percentage of Contribution: *Candidate 70%, Faisal Khan 12%, Vikram Garaniya 8%, Rouzbeh Abbassi 10%.*

We the undersigned agree with the above stated “proportion of work undertaken” for each of the above published (or submitted) peer-reviewed manuscripts contributing to this thesis:

Signed:

Prof Faisal Khan
Primary Supervisor
Centre for Risk, Integrity and Safety Engineering (C-RISE)
Memorial University of Newfoundland

Date: 23/03/2018

Dr Vikram Garaniya
Co-Supervisor
National Centre for Maritime Engineering and Hydrodynamics (NCMEH)
University of Tasmania

Date: 23/03/2018

Dr Rouzbeh Abbassi
Co-Supervisor
National Centre for Maritime Engineering and Hydrodynamics (NCMEH)
University of Tasmania

Date: 23/03/2018

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Abstract

Over the years, there has been a significant increase in both size and complexity of processes in marine and offshore operations. One example of maritime operations is that of large-scale Floating Liquefied Natural Gas (FLNG) processing facilities. Accidents in such facilities can be very complex and would be best characterised by evolving scenarios. This thesis reports on the development of a new methodology to incorporate evolving scenarios in a single model and predicts the likelihood of an accident. The methodology comprises; (a) evolving scenario identification, (b) accident consequence framework development, (c) accident scenario likelihood estimation, and (d) ranking of the scenarios. Resulting events in the present work are modelled using a Bayesian Network (BN) approach, which represents accident scenarios as cause-consequences networks. The methodology developed in this thesis is compared with case studies of ammonia and Liquefied Natural Gas (LNG) from chemical and offshore process facility, respectively. The proposed method can differentiate the consequence of specific events and predict probabilities for such events along with continual updating of the consequence probabilities of fire and explosion scenarios being taken into account. The developed methodology can be used to envisage evolving scenarios that occur in the offshore oil and gas processing industry. However, with further modification, it can be applied to different sections of marine industry to predict the likelihood of such accidents.

Maritime transportation poses risks regarding possible accidents resulting in damage to vessels, crew members and to the ecosystem. The safe navigation of ships, especially in Arctic waters, is a growing concern to maritime authorities. This study proposes a new risk model to investigate the possibility of marine accidents such as collision,

foundering and grounding. The model is developed using the BN. The proposed risk model has considered different operational and environmental factors that affect shipping operations. The application of the model is demonstrated through a case study of an oil-tanker navigating the Northern Sea Route (NSR). By running uncertainty and sensitivity analyses of the model, a significant change in the likelihood of the occurrence of accidental events is identified. The model suggests ice effect as a dominant factor in accident causation. The case study illustrates the priority of the model in investigating the operational risk of accidents. The developed methodology can be used to investigate the possibility of preventing and mitigating ship accidents in harsh and cold environments.

Collision avoidance in narrow channel is critical if no early warning is provided. In this thesis, a dynamic risk management system is proposed for the marine vessel so that it can be useful by warning the operator of a vessel of a potential collision threat while travelling along narrow trafficway. This model estimates the level of risk by taking into consideration vessel kinematics, different operational and environmental factors as well as human factors in a confined area and provides early warning. Five decision-making skills viz. general skills, management training, technical knowledge, emergency skills and sailing experience are employed as requirements in an emergency. The applicability of the proposed methodology has been demonstrated through two case scenarios in a narrow channel. The probability obtained through the proposed methodology can be used to make a real-time decision, such as situation assessment, appropriate and immediate action followed by the evasive action. The simulated result shows the increasing level of risk as the probability of warning level increases. Similarly, lower risk decreases as the situation crosses that threshold. The estimated risk allows early warning to take appropriate preventive and mitigative measures to avoid a collision and thus enhance the overall safety of shipping operations.

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Nomenclature

D	Total distance	[m]
d_{min}	Remaining distance	[m]
d_{safe}	Minimum safe distance	[m]
H	Height	[m]
H_s	Significant wave height	[m]
t	Time	[s]
T	Wave period	[s]
T_z	Zero up-crossing wave period	[s]
U_{10}	Wind Speed 10m above the surface	[m/s]

Abbreviations

ABS	American Bureau of Shipping
AD	Asset Density
AHI	Accident Hazard Index
AIS	Automatic Identification System
ALARP	As Low As Reasonably Practicable
AMC	Australian Maritime College
AMSA	Australian Maritime Safety Authority
BLEVE	Boiling Liquid Expanding Vapor Explosion
BN	Bayesian Network
CAS	Collision Avoidance System
CPT	Conditional Probability Table
CNG	Compressed Natural Gas
DAG	Directed Acyclic Graph
ECDIS	Electronic Chart Display and Information System
Eq.	Equation
FLNG	Floating Liquefied Natural Gas
FPSO	Floating Production Storage and Offloading
FSA	Formal Safety Assessment
GPS	Global Positioning System
HAZOP	Hazard and Operability Study
HIRA	Hazard Identification and Ranking
HSE	Health and Safety Executive
ICORELS	International Commission for the Reception of Large Ships
IM	Importance Factor
IMO	International Maritime Organisation
JTSB	Japan Transport Safety Board
JWC	Joint War Committee
LFL	Lower Flammable Limit
LMA	Lloyd's Market Association
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas

MAIB	Marine Accident Investigation Branch
MARCS	Marine Accident Risk Calculation System
MCAR	Marine Collision Avoidance Risk
MCAS	Maximum-Credible Accident Scenarios
MTDC	Minimum Distance to Collision
NAVTEX	Navigational Telex
NSR	Northern Sea Route
NTSB	National Transportation Safety Board
OOBN	Object-Oriented Bayesian Network
PD	Population Density
PDF	Population Distribution Factor
PIANC	Permanent International Association of Navigation Congresses
PIF	Performance Influencing Factor
PRA	Probabilistic Risk Assessment
QRA	Quantitative Risk Analysis
RADAR	Radio Detection and Ranging
RPT	Rapid Phase Transformation
SBWR	Shipborne Wave Recorder
SME	Subject Matter Expert
UDA	Unacceptable Damage Area
UFL	Upper Flammable Limit/Unacceptable Financial Loss
VCE	Vapor Cloud Explosion
VHF	Very high frequency
WPF	Weather Probability Factor
WMO	World Meteorological Organization

Chapter 1: Introduction

1.1. Background

Maritime operations are very difficult to make completely safe and risk free. Accidents can expose ship owners and operators, as well as the public, to risk. The nature of an accident can be troublesome as the consequences may lead to loss of life, structural failure, serious injuries to people, disruption of operation and damage to the environment. In marine systems there are two types of objects; moving (e.g., ships and boats) and fixed (e.g., offshore oil and gas platform and wind farms). Therefore, major marine and offshore accidents can be categorised into three groupings, such as collision between (i) moving to moving object, (ii) moving to fixed object, and (iii) other accidents (e.g., grounding, capsizing, fire and explosion and structural failure). Marine accident model of these three types of accident is shown in Figure 1–1.

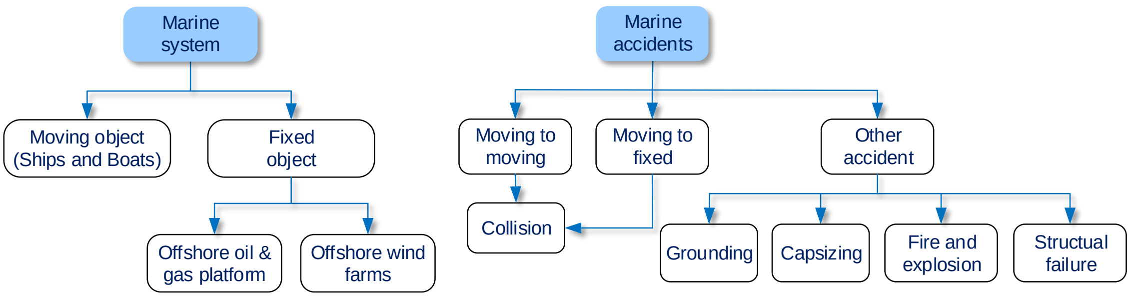


Figure 1–1: Marine system and type of accidents.

Ship to ship collision or collision with a fixed object such as an offshore platform can be catastrophic. Collision can lead to fire and explosion and as a result, grounding and capsizing could happen. According to Bottelberghs (1995), marine accidents fall under the scenarios of collision, fire and explosion, flooding, and grounding. Figure 1–2 illustrates the four types of marine accidents, viz. (i) fire and explosion, (ii) collision, (iii) capsizing and, (iv) grounding.

Figure 1–2: Four different types of marine accidents.

According to the Transportation Safety Board (TSB) of Canada (TSB, 2017), the most frequent types of shipping accidents in 2016 were fire/explosion accidents (17%), collisions (33%), and groundings (25%), as illustrated in Figure 1–3. The total number of ship collisions increased by 12% from the five-year average (2011-2015) from 78 to 87 in 2016. Similarly, fire/explosion accidents increased by 24% from the five-year average from 35 to 44 in 2016.

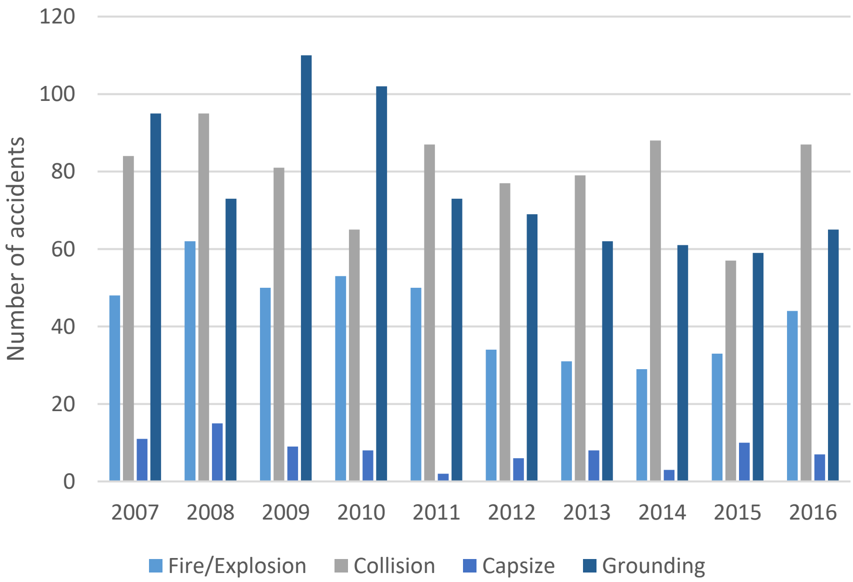


Figure 1–3: Marine shipping accidents (2007-2016).

Human error effect is recognised as one of the recurrent causal factors for marine ship collision. According to an MAIB (2004) report, the most common contributory factors in 33 collisions that happened during the period 1994-2003 were poor lookout (65%) and poor use of radar (73%).The International maritime organization (IMO) has made significant efforts to promote safety at sea in the marine shipping industry (O'Neil, 2003). However, a large number of accidents occur every year needing attention and lessons need to be learnt from past marine accidents (Uğurlu, 2011). Environmental protection agencies are now concerned about protecting the marine environment by promoting awareness to marine casuals and people associated with marine businesses.

1.2. Problem statement

The risk of fire and explosion due to a major or minor accident is very common in offshore operations. In offshore industry, processing accidents such as fire and explosion are often caused by equipment malfunction, process deviation, structural failure, and human error (Pula et al., 2005). Inadequate control of these factors can lead to an increase in the incidence of industrial accidents. There is a lack of knowledge to incorporate evolving scenarios in a single model and predict the likelihood of an accident (e.g., fire and explosion). In a processing accident, minor or severe damages can cause fatalities, financial loss as well as environment damages. Besides damages, it is necessary to identify any probable accident event, the magnitude of damages and its impact on the environment to estimate and envisage prospective losses. Hence, identification and ranking of potential damages are needed to ensure maximum safety.

The Northern transport corridor, known as the Northern Sea Route (NSR) in the Arctic region, is one of the potential trade routes connecting major Asian and European ports. The presence of sea ice, extremely low temperatures and drifting icebergs has made this region mostly inaccessible for marine transportation and poses threats to mariners and the current ship technologies (Ellis and Brigham, 2009). Previous studies confirm that increasing traffic of oil tankers in the Barents Sea will result in a significant number of accidents if further maritime safety measures are not attained (NME, 2011). The safe navigation of ships, especially in the Arctic waters, is of growing concern to maritime authorities. However, limited research has been conducted on the effect of both cold and harsh environmental conditions on shipping accidents in this region. Integrated accident models based on different types of accidents for the NSR are quite limited. Recorded data of wave height and wind speed for the NSR have never been considered in the literature or accident analysis. Thus, conventional ship accident models developed for Arctic regions may not address the integrated accident events such as ice-ship collision, foundering and grounding, simultaneously considering recorded data of five sea states.

Collision avoidance is an essential task for any transportation system as well as in many other applications. A marine vessel needs to maintain safe distance in open water as well as in a confined channel. In the presence of a stationary or non-stationary vessel/object a vessel needs to react immediately to avoid a potential collision and it would be alarming if no early warning was provided. Marine vessels are equipped with the latest radar system; however, they lack the latest sensors, similar to an auto vehicle to receive similar support in a confined area where vessels battle for room to manoeuvre safely. There is a need for a dynamic risk-based model to predict the level of risk and take effective action in real-time considering vessel kinematics, operational and environmental conditions as well as human factors. Thus, conventional collision alert models developed for confined areas may not address the criteria discussed above.

1.3. Knowledge and technical gaps

Marine and offshore accidents can lead to evolving scenarios, such as gas leakage which may result in a vapor cloud explosion (VCE), jet fire, pool fire, fireball and boiling liquid expanding vapor explosion (BLEVE). Previous studies by Kim and Salvesen (2002), Koo et al. (2009) and Skarsbo (2011) limit focus on individual fire and/or explosion modelling, ignoring evolving scenarios. However, a potential pool fire scenario is completely ignored (Dadashzadeh et al., 2013b). Another study by Koo et al. (2009) on an LNG terminal focused on pool fire modelling. Hence, no consideration was given to VCE or other possible interactions such as jet fire (Dadashzadeh et al., 2013b). Fire and explosion accident scenario analysis can be ranked according to their credibility to identify the most hazardous event. Literature review on accident hazard index has shown that identification and ranking of process hazards mostly focus on Dow Index (Dow, 1967-87; Scheffler, 1994), Mond Index (GDG, 1970-85), Toxicity Index (Tyler et al., 1995) and accident hazard index referred to as HIRA (Hazard Identification and Ranking) by Khan and Abbasi (1997). These hazard indices are limited to only industrial sites ignoring surrounding population, environment and assets yet, these indices have a strong influence on deciding adverse impacts caused by a potential accident. Christen et al. (1994) took an initiative to rank the severity of past accidents on a scale of 0-1 without envisaging the damage potential from similar types of accident in different premises. This ranking scale was considered as the most advanced approach by Khan and Abbasi (1997) though site specific attributes were not considered during the operation of this scale. Keller et al. (1985) and Wyler and Bohnenblust (1991) also recommended a rank-based system to rank past accidents yet forecasting of similar types of accident was overlooked. After reviewing above mentioned approaches, Khan and Abbasi (1997), proposed accident hazard index (AHI) that characterized accident consequences on a standard scale of 1-10. It overcame past limitations by incorporating different direct impact parameters such as surrounding population, asset, ecosystem and indirect impact of different environmental media such as soil, water and air to the model. However, the AHI method is not able to model the evolving scenarios rather it considers individual consequences and ranks them based on their credibility.

In maritime risk and consequence assessment, several methods have been applied to estimate the causation probability of shipping accidents. Fujii and Shiobara (1971) introduced one of the most common approaches to estimate the number of ship collisions, where the number of collisions is calculated as a product of the number of geometrical collision candidates and a causation probability. Macduff (1974) initially proposed a ship collision and grounding model based on available historical accident records. However, it lacked a clear understanding of accident causes. Risk analysis tools such as fault trees were developed to estimate the causation probability of collision events (Pedersen, 1995; Rosqvist et al., 2002). Marine Accident Risk Calculation System (MARCS) was also developed based on fault tree analysis while considering major shipping accidents such as collisions, powered grounding, drift grounding, foundering and fire and explosions by Fowler and Sørgård (2000). Danish institution COWI (2008) proposed formal safety assessment (FSA) methodology for sea traffic taking into account collisions and groundings. Martins and Maturana (2010) applied fault tree analysis to assess the collision and grounding probability using FSA method. Zaman et al. (2014) estimated the risk of collision in the Malacca Strait using the FSA approach. Merrick et al. (2000) developed a Probabilistic Risk Assessment (PRA) technique considering expert judgment to assess the accident risk in the Prince

William Sound. Van Dorp et al. (2001) developed maritime accident event chain which included collision, grounding and fire/explosion using available data combined with expert judgment. Montewka et al. (2010) proposed a geometrical model to assess the likelihood of ship collisions. A collision probability model based on Monte Carlo simulation technique was developed by Goerlandt and Kujala (2011). Later, it was used in evaluating the risk of tanker collisions in the Gulf of Finland (Goerlandt et al., 2011). a probabilistic approach was proposed to assess the risk and sustainability associated with ship collision by Dong and Frangopol (2014). Goerlandt et al. (2015) developed a ship collision alert system to measure ship collision risk based on fuzzy approach and expert elicitation. Banda et al. (2015) visualised the accident risks through a hazard identification model in the Finnish-Swedish winter navigation system. Sormunen et al. (2015) investigated chemical tanker collision as a case study by taking into account data uncertainties. Montewka et al. (2014) proposed BN framework for ship-ship collisions in the open sea, evaluated the probabilities of these events and finally, determined the severity of a collision. Goerlandt and Montewka (2015) developed a Bayesian network model and applied it to a case study of the oil spill from a tanker to quantify the risk. Mazaheri et al. (2016) proposed an evidence-based and expert-supported Bayesian Belief Networks (BBNs) for assessing the probability of ship-grounding accidents. Fu et al. (2016) developed a causal probabilistic model to predict the probability of a ship stuck in ice in the Arctic waters using the BBNs. In this causal model, a set of input parameters, such as hydro-meteorological conditions (air temperature, ice concentration, ice thickness, sea temperature, wave height and wind speed), along the analysed route were considered. Khan et al. (2017) proposed an Object-Oriented Bayesian Network (OOBN) model to predict ship-ice collision probability considering navigational, operational and human factors.

Among ship accidents, ship-ship collision has been the focus of many related studies in recent years (Goerlandt et al., 2015; Goerlandt et al., 2012a; Montewka et al., 2011a; Montewka et al., 2012; Montewka et al., 2011b; Montewka et al., 2010; Qu et al., 2011). Fujii et al. (1970) and Macduff (1974) used the concept of collision diameter which is defined as the contact of two vessels at a distance (Pedersen, 1995). Gluver and Olsen (1998) utilised ship domain approach to assess ship to fixed object collision. Fowler and Sørgård (2000) used the critical situation criteria, defined as a close encounter of two vessels within a certain distance. Tran et al. (2002) developed a unified collision avoidance system for marine operation called MANTIS. Kaneko (2002) proposed a collision model to encounter probability estimation which, defines a critical area in a rectangular and circular shape around a vessel with violation of that area meaning a collision. Pedersen (2002) published a series of papers based on collision assessment of a ship to a fixed object. Montewka et al. (2010) proposed the MDTC (Minimum Distance to Collision) geometrical model for the ship to ship collision probability estimation. Mou et al. (2010) established a risk assessment model and used the automatic identification system (AIS) data to study collision avoidance in busy waterways by taking into consideration ship collision data. Qu et al. (2011) studied ship collision risks in the Singapore Strait by considering real-time ship location and vessel speed. Montewka et al. (2011a) defined a critical situation as a close encounter of two vessels within a distance of 0.5 Nm and considered this value as constant, regardless of any contact between those two vessels. The Airborne Collision Avoidance System (ACAS) was already introduced in (Baldauf et al., 2014;

Baldauf et al., 2015) for maritime domain. Further this method was extended as Maritime Traffic Alert and Collision Avoidance System (MTCAS) in (Baldauf et al., 2017; Denker et al., 2016). According to Baldauf et al. (2017), to trigger a perfect collision alarm very much needed a comprehensive network of sensors to provide accurate and reliable data of own vessel, marine environment and targets in the vicinity. Szlapczynski and Szlapczynska (2017) presented a Collision Threat Parameters Area (CTPA) display based technique featuring a manoeuvre simulation mode to assist the navigator in advance to see the results of a planned manoeuvre (combinations of own course and speed with respect to time as well as target-colliding and landmass-colliding). Szlapczynski and Krata (2018) further extended the method by utilising detailed modelling of own ship dynamics viz. course alteration manoeuvres and supports navigation for harsh weather conditions.

Based on the challenges remaining in the problem of fire and explosion modelling for marine and offshore structures, integrated accident model for the NSR and the collision avoidance in narrow channel discussed above, the following research gaps have been identified:

- Previous studies are limited to individual fire and/or explosion modeling, ignoring evolving scenarios.
- Most credible accident scenarios are not ranked in most studies.
- An up to date consequence modelling framework needs to be developed to address fire and explosion consequences based on release condition (primary causes).
- Integrated accident models based on different types of accidents for the cold region such as NSR are quite limited.

- Recorded data of wave height and wind speed for the NSR are not available in present literature and have never been considered for accident analysis where appropriate.
- Collision alert system for marine vessel, similar to an auto vehicle, would be an updated approach for marine industry to detect potential hazard in narrow channel and hence couple decision-making skills.
- Use of OOBN are limited to address complex network available for collision alert systems
- Conventional risk analysis approaches are mostly used to identify potential causes and consequences.

1.4. Research objectives

This work aims at a better understanding of the problem of marine process accidents in processing facility and transportation accidents in open sea and in narrow channel. The specific research objectives of this work are:

1. to achieve an in-depth understanding of evolving scenarios in marine and offshore operations;
2. to develop a novel dynamic accident model applicable to cold environment;
3. to develop a novel model to integrate potential accidents applicable in maritime operations; and
4. to demonstrate the application of the developed approaches and methodologies through illustrative examples or case studies.

1.5. Research questions

The research questions answered by this work are:

1. How to quantify what can go wrong in any marine and offshore operation considering process and transportation accidents?
2. How to develop a dynamic accident model for marine and offshore opeartions?
3. How to adopt a probabilistic approach for marine uncertainty data analysis?
4. How to demonstrate the accident model in real-life example?
5. How to integrate different type of marine transportation accidents in a single combined model?

1.6. Novelty and contribution

Following contribution has been made in this research:

- An integrated fire and explosion model is developed to address evolving scenarios and identify the most credible scenarios and rank them accordingly.
- An up to date consequence modelling framework is developed applicable to fire and explosion events.
- An integrated dynamic risk model is developed for the cold region.
- A dynamic collision alert system, marine collision avoidance risk (MCAR), is developed for the narrow channel.

1.7. Scope and limitations of the study

The scope of this study was limited to investigating marine process accidents in processing facility and transportation accidents in open sea and in narrow channel. In the first part of the work, literature review of different marine and offshore accidents is performed. During the literature review, accident models applicable to marine and offshore accidents are considered. In the first part of the work, emphasis is given to fire and explosion consequences. In the second part of the work, emphasis is given to ship accidents such as collision, foundering and grounding in the Arctic region. A dynamic risk-based model is developed to integrate these accidents into a single combined model. In the final part of the work, emphasis is given to collision alert system applicable in narrow channel.

The overall objectives and associated tasks are listed in Figure 1–4.

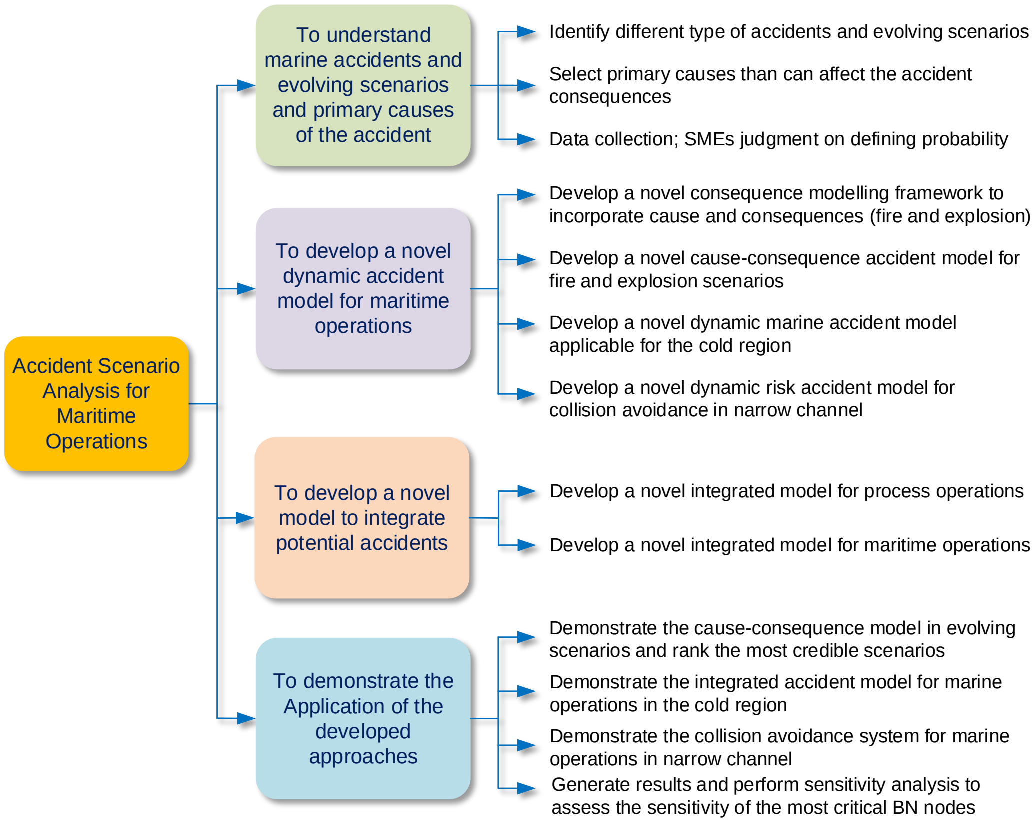


Figure 1–4: Objectives and associated tasks of this research.

1.8. Thesis organisation

This thesis is comprised of three main chapters compiled from two journal articles that have been accepted for publication and one other article currently under review. The relevant publishing details are given at the beginning of each chapter. A flowchart of the research conducted during this PhD study is presented in Figure 1–5.

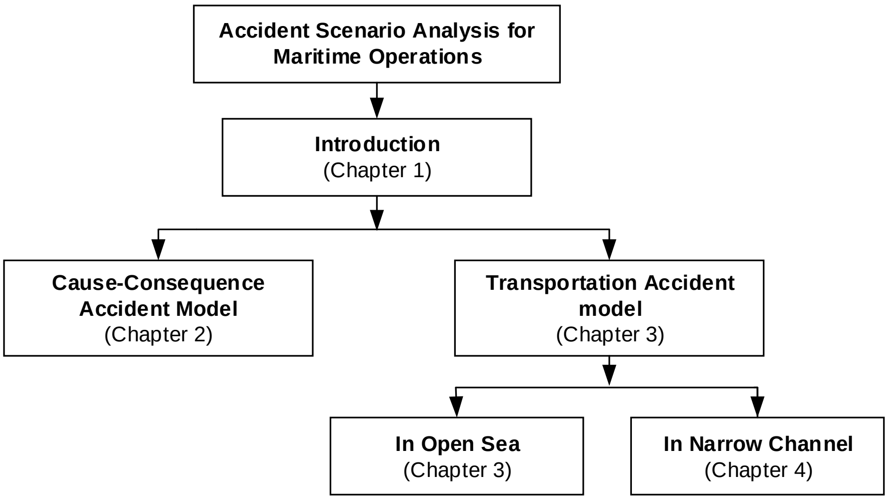


Figure 1–5: A flowchart showing thesis organisation.

An outline of each chapter is presented below.

- Chapter 2 emphasises cause-impact accident model and describes the integration of accident consequences and the potential outcome through accident case scenarios. **Research objectives 1 – 4** are addressed in this chapter.
- Chapter 3 emphasises marine transportation risk in Arctic waters. This chapter presents a dynamic risk-based model to analyse shipping accidents in Arctic waters to reduce the risk of accidents considering particular environmental and operational conditions. **Research objectives 1 – 4** are addressed in this chapter.
- Chapter 4 focuses on a collision avoidance model only applicable in a narrow channel to estimate the level of risk and hence, real-time decision making in the presence of stationary and non-stationary objects en-route. **Research objectives 1 – 2** and **4** are addressed in this chapter.

- Chapter 5 presents the main research conclusions of this study and recommendations for future work.
- Appendix A illustrates a peer-reviewed conference paper submitted to the 12th International Offshore and Polar Engineering (ISOPE) Pacific/Asia Offshore Mechanics Symposium (PACOMS). The paper presents a probabilistic approach to foresee the most probable accident scenario in complex offshore processing facilities by considering the evidence of primary causes.

Chapter 2: A network based approach to envisage potentials accidents in offshore process facilities

This work presented in this chapter has been published in the journal of *Process Safety Progress*. The paper has been edited for inclusion into this thesis to improve readability. The citation for this research article is:

Baksh, A.-A, Abbassi, R., Garaniya, V. and Khan, F. (2017). A network based approach to envisage potential accidents in offshore process facilities. *Process Safety Progress.* 36: 178-191. DOI:10.1002/prs.11854.

Abstract

Envisaging potential accidents in large scale offshore process facilities such as Floating Liquefied Natural Gas (FLNG) is complex and could be best characterized through evolving scenarios. In the present work, a new methodology is developed to incorporate evolving scenarios in a single model and predicts the likelihood of accident. The methodology comprises; a) evolving scenario identification, b) accident consequence framework development, c) accident scenario likelihood estimation, and d) ranking of the scenarios. Resulting events in the present work are modelled using a Bayesian network approach, which represents accident scenarios as cause-consequences networks. The methodology developed in this article is compared with case studies of ammonia and Liquefied Natural Gas from chemical and offshore process facility respectively. The proposed method is able to differentiate the consequence of specific events and predict probabilities for such events along with continual updating of consequence probabilities of fire and explosion scenarios taking

into account. The developed methodology can be used to envisage evolving scenarios that occur in the offshore oil and gas process industry; however, with further modification it can be applied to different sections of marine industry to predict the likelihood of such accidents.

2.1. Introduction

FLNG is the most recent addition to floating process facilities which is dynamic in nature and can be characterized by complex subsystems, distributed processes, uncertainty and a high degree of automation. Chemicals or hydrocarbon release from these facilities can escalate to catastrophic events which may result in casualties and significant damages to the environment and coastal marine ecosystems (HSE, 1996). The production of hydrocarbons in the offshore process industry has the potential for events involving major fires and/or explosions (Krueger and Smith, 2003). This is reflected in examples of several offshore accidents, such as the 1988 Piper Alpha incident in the UK North Sea (Paté-Cornell, 1993), capsizing and sinking of the Petrobras P-36 in Roncador, Brazil (Atherton and Gil, 2010), explosion on the Cidade de São Mateus (PGJ, 2015), and fire on the Pemex Abkatun Alpha platform in the Gulf of the Mexico (Turner-Neal, 2015). According to Paté-Cornell (1993), the Piper Alpha tragedy caused 165 deaths due to an explosion after releasing of hydrocarbons. Atherton and Gil (2010) reported on series of explosion that had occurred in the Petrobras P-36 platform claiming 11 lives and a loss of up to $1 billion a year (Keep, 2001). Recent explosion on Floating Production Storage and Offloading (FPSO) unit of Cidade de São Mateus caused 5 deaths and 4 missing crews. According to the Pemex press release, a fire outbreak in the Abkatun Alpha platform killed 4 people and injured as many as 16 others.

In process accidents, hydrocarbon leaks or release of materials may contribute more or less potential damage to accidents. For instance, on October 1944, a LNG tank in Cleveland, Ohio failed and released its entire contents, resulting in a vapor cloud explosion (VCE) from an unknown ignition source (Yang et al., 2011). In addition it caused the deaths of 130 people (Duerr, 2014). The flange leaked, and the presence of an ignition source caused multiple consequences including fireball and jet fire followed by VCE. Another LNG spill in 2004 in the Skikda LNG plant, Algeria triggered multiple explosions due to excessive pressure in an adjacent boiler and claimed 27 lives and injured 80 (Woodward and Pitblado, 2010). Due to a hydrocarbon release in the BP's Texas City refinery in 2005, an explosion occurred which killed 15 people and injured as many as 180 others (CSB, 2007). After the release, VCE occurred followed by pool fire (Kalantarnia et al., 2010; Khan and Amyotte, 2007). The leading cause stated is insufficient and improper knowledge to control the release and responses (Broadribb, 2006). Compressed Natural Gas (CNG), LNG and Liquefied Petroleum Gas (LPG) are identified as alternative fuels to liquid petroleum (Olanrewaju et al., 2013). As the demand for clean energy is uprising day by day, the shipping industry, especially flammable gas carriers (e.g., CNG, LNG, LPG and FLNG facility), is facing heavy pressure to avoid any disaster. In terms of design, construction, work force, operation and maintenance, natural gas carriers have proven their safety record. Due to a significant number of safety measures, accident frequencies are much lower for natural gas carriers when compared to other vessels (Håvold, 2010; Vanem et al., 2008; Yeo et al., 2016). Accident occurrences in LNG and LPG process facilities are well explained in literature (Atherton and Gil, 2010; CEC, 2015; Dadashzadeh et al., 2013a; HSE, 1996, 2005; Khan and Abbasi, 1999; Kletz, 1991).

In process industries, some accidents (e.g., leakage from a pipe, and crack from elbow) occur more frequently and can cause minor damage whilst other type of accidents (e.g., process tank failure, and overflow of a vessel) occur less frequently and can escalate into major accidents and cause potential losses. Incident, such as gas leakage is a common issue in offshore oil and gas process facilities and this event may subsequently lead to different credible accidents such as VCE, jet fire, pool fire, fireball and boiling liquid expanding vapor explosion (BLEVE). In most cases, these types of events may have ended in catastrophic accidents. It has been reported that 59% of these types of events have resulted in fire, 35% in explosions and 6% in gas clouds (Gómez-Mares et al., 2008). As stated by Bottelberghs (1995), marine accidents are comprised of scenarios including collision, fire and/or explosion, flooding and grounding. Focus on previous studies (fire and explosion) by Kim and Salvesen (2002), Koo et al. (2009) and Skarsbo (2011) were limited to individual fire and/or explosion modeling, ignoring evolving scenarios. Kim and Salvesen (2002) conducted a study on LNG vapor release which was addressed as a possible VCE. However, a potential pool fire scenario is completely ignored (Dadashzadeh et al., 2013b). Another study by Koo et al. (2009) on a LNG terminal focused on pool fire modeling. Hence, no consideration was given to VCE or other possible interactions such as jet fire (Dadashzadeh et al., 2013b). It is therefore essential to consider potential consequences as a leak or release event may lead to multiple consequences. A review of past accidents (CEC, 2015; Crowl, 2010; CSB, 2007, 2008; Dadashzadeh et al., 2013b; Håvold, 2010; Khan and Abbasi, 1999; Kletz, 1991; Kujala et al., 2009; NTSB, 1983; Paté-Cornell, 1993; PC, 2011; Rajendram et al., 2015) and models (Abbassi et al., 2016; Ale et al., 2008; Ale et al., 2006; Ale et al., 2009; Antão et al., 2008; Antão and Soares, 2006; Antão and Soares, 2008; Baksh et al., 2015; Kim and Salvesen, 2002;

Koo et al., 2009; Røed et al., 2009; Skarsbo, 2011; Vanem et al., 2008; Wells, 1997; Yeo et al., 2016) demonstrates the need to evaluate the entire accident sequence to mitigate the impact, develop appropriate response methods, and prevent accidents by designing safety into the system.

Based on accident scenario analysis of potential accidents, it is necessary to rank them according to their credibility, so the hazardous event can get most priority. Literature review on accident hazard index has shown that identification and ranking of process hazards mostly focused on Dow Index (Dow, 1967-87; Scheffler, 1994), Mond Index (GDG, 1970-85), Toxicity Index (Tyler et al., 1995) and accident hazard index mentioned as HIRA (Hazard Identification and Ranking) by Khan and Abbasi (1997). These hazard indices are limited to only industrial sites ignoring surrounding population, environment and assets; however, these indices have a strong influence on deciding adverse impact caused by a potential accident. Christen et al. (1994) took an initiative to rank the severity of past accidents on a scale of 0-1 without envisaging the damage potential from similar type of accidents in different premises. This ranking scale was considered as the most advanced approach by Khan and Abbasi (1997); however, site specific attributes were not considered during the operation of this scale. Keller et al. (1985) and Wyler and Bohnenblust (1991) also recommended a rank-based system to rank past accidents yet forecasting of similar type of accident was overlooked. After reviewing above mentioned approaches, Khan and Abbasi (1997), proposed accident hazard index (AHI) that characterized accident consequences on a standard scale of 1-10. It overcame past limitations by incorporating different direct impact parameters such as surrounding population, asset, ecosystem and indirect impact of different environmental media such as soil, water and air to the model.

However, the AHI method is not able to model the evolving scenarios rather it considers individual consequences and rank them based on their credibility. After reviewing past accident investigation, the authors believe that there is a need for a new approach to envisage the most credible accident scenarios based on primary causes such as release event, release condition, type of discharge, type of dispersion, type of ignition and area of congestion at release site and to rank them accordingly. Therefore, in this study, a network based approach is undertaken to overcome common issues that exist in conventional methods. The proposed method is able to differentiate the consequence of specific events and predict probabilities for such events. The updating process of consequence probabilities of fire and explosion scenarios are depending on new information of primary causes as they added to the system. Case studies from past accidents in chemical and offshore process industry are taken into consideration to demonstrate the application of the developed methodology. This method is meant to be useful for evolving scenarios, specifically for individual fire and/or explosion consequences on process facility that may occur due to deviation of any primary causes. The focus of the current study is on the integration of accident consequences and the potential outcome through accident case scenarios.

This following section is organized as follows: section “Brief review of risk assessment methodologies” deliberates brief review of risk assessment methodologies in marine and offshore facilities; section “Quantitative risk analysis of offshore fire and explosion based on root causes” discusses about Quantitative risk analysis of offshore fire and explosion and the developed methodology for the selected scenario. In section “Application of the methodology: case studies” two case studies are provided to demonstrate the application of the proposed methodology; section "Conclusion" gives the conclusions.

2.2. Brief review of risk assessment methodologies

Risk assessment is often considered as an aid to the decision-making process (IMO, 2002). In order to ensure safety, it is essential to reduce the risk and mitigate the occurrence of marine and offshore accidents to a level that is as low as reasonably practicable (ALARP). Due to high cost of offshore processing plant, severity of fire and/or explosion, and complexity of marine environment, it becomes an imperative necessity to determine fire and/or explosion risk analysis (HSE, 2005). As stated by Wang et al. (2015b), three kinds of researches are carried out worldwide on offshore fire and/or explosion risk analysis which comprises; (i) statistical methods, (ii) use of commercial software, and (iii) integration of new theory with traditional risk assessment methods. Among these methods, statistical methods are used to predict fire and/or explosion risk based on historical data (Paik and Czujko, 2009). As mentioned by Vinnem (2007), the study of risk assessment is an important area of offshore processing facilities as it includes, (1) hazard identification, (2) cause and probability analysis, (3) accidental scenarios analysis, (4) consequence, damage and impairment analysis, (5) escape, evacuation and rescue analysis, (6) fatality risk assessment, and (7) analysis of risk reducing measures. Risk assessment process demonstrated in Figure 2–1 is adopted from Arendt (1990).

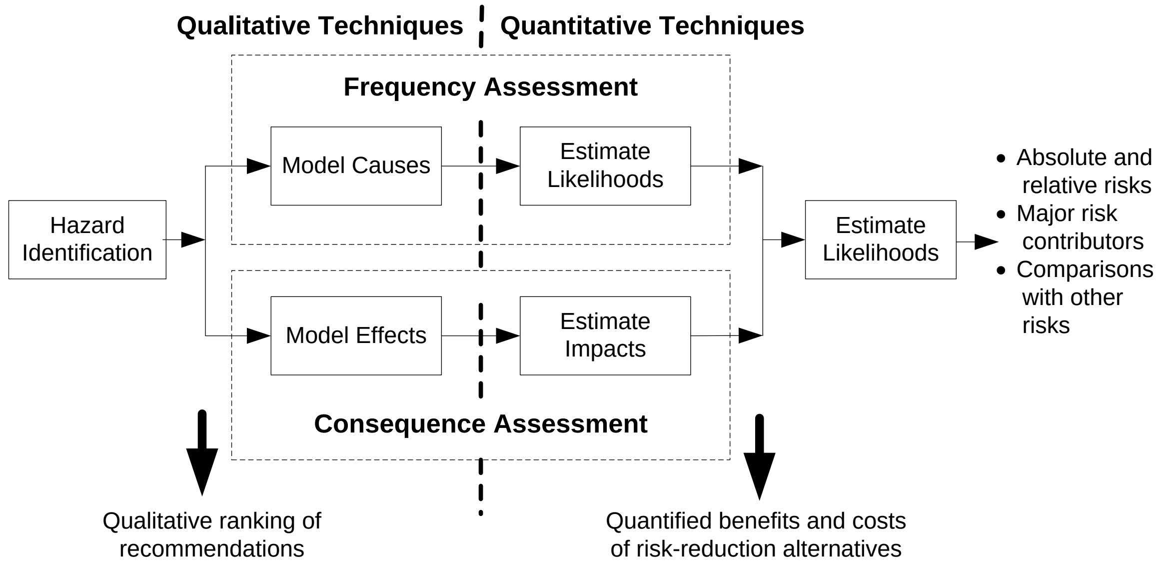


Figure 2–1: The risk assessment process.

In the offshore oil and gas industry, quantitative risk analysis (QRA) has played an important role for decision-support in the planning phase for more than 20 years (Røed et al., 2009). It is often considered as an approach to access and manage safety of the process system. As referred by Pula et al. (2006), this technique includes four major steps: (1) hazard identification, (2) consequence analysis, (3) frequency assessment, and (4) risk quantification. Consequence analysis is considered as an integral part of risk assessment process. It is mentioned in the quantitative risk analysis guidelines that the complexity of a QRA builds on the events scenario based on available data and consequence information (CCPS, 2000). Depending on event scenarios, several mathematical models, viz. source models, fire and explosion models, and toxic gas models are applicable for consequence assessment (Khan and Abbasi, 1998b).

A literature review is carried out to identify risk analysis methods of offshore fire and/or explosion. Khan (2001) proposed, maximum-credible accident scenarios (MCAS) method to shortlist the credible accident scenarios based on their consequences and the likelihood of occurrence. The maximum credible accident represents maximum potential damage, viz. physical, financial and environmental caused by an accident. To account the MCAS method effectively, the most relevant case scenario from each unit requires to be shortlisted for the purpose of the study. There are four steps to follow in the MCAS method, i) develop all plausible accident scenarios, ii) calculate damage radii for each scenario, iii) estimate probability for each accident scenario, iv) classify and list the credible scenario. In second step, damage radii can be calculated using quantitative hazard indices. This approach helps to enhance the overall effort without compromising the accuracy of the study. Krueger and Smith (2003) demonstrated a scenario-based approach to calculate potential impacts of credible fire scenarios on the platform process equipment, structural members, and safety systems. Pula et al. (2005) proposed fire consequence model as a combination of submodels (e.g. individual fire models, and human impact model). Afterwards, Pula et al. (2006) demonstrated a revised version of the basic model. The performance result of the consequence model was compared with the output of computer software. Ale et al. (2006) developed a causal model for air transport safety to find causes of incidents and accidents. Ale et al. (2008) and Ale et al. (2009) demonstrated sequential logic and causal models followed by a safety barrier approach, which was translated into event tree, fault tree and Bayesian Belief Nets (BBN) to evaluate causal sequences and quantify risks. Vinnem (2013) proposed failure models for hydrocarbon leaks for offshore process plant based on 70 major hydrocarbon leaks. Ale et al. (2014) developed a dynamic risk management tool based on BBNs for the hydrocarbon industry to observe risk in real-time. Baksh et al. (2015) have shown non-sequential network by implementing BN to calculate end events probabilities using case studies from offshore process facility. Recently, Yeo et al. (2016) have proposed a dynamic risk assessment model using BN to investigate different risk factors associated with LNG offloading procedures that may result in collision and grounding.

2.3. Quantitative risk analysis of offshore fire and explosion based on root causes

In the proposed scenario-based methodology, identification of evolving scenarios is the first step which includes shortlist of credible accident scenarios and identifying potential consequences including contributing factors. For instance, in a LNG process facility deviation from a normal operation can cause potential damages which consists of operating pressure in process facility, release rate of the liquid or gas, ignition source (e.g., engine room, and boiler room), temperature inside the facility, and wind speed outside of the process operation. After identification of evolving scenarios and potential consequences, the next step is to develop a consequence modelling framework. The aim of developing this framework is to identify the potential consequences for each specific scenario based on primary causes. The likelihood estimation of each specific accident is carried out in the following step by developing and implementing a BN for each scenario. For a given scenario, identification of significant losses such as fatalities, financial and environmental losses are also incorporated in subsequent steps using MCAS method (see details in Khan (2001)). These losses vary depending on a particular accident scenario. Therefore, consequence probabilities are estimated for each selected scenario. In the final step, the methodology ranks each specific scenario according to their priority based on potential damages, viz. fatalities, financial and environmental loss. The overall process of the developed methodology is illustrated in Figure 2–2. The main steps considered in the developed methodology are discussed in more details in the following sections.

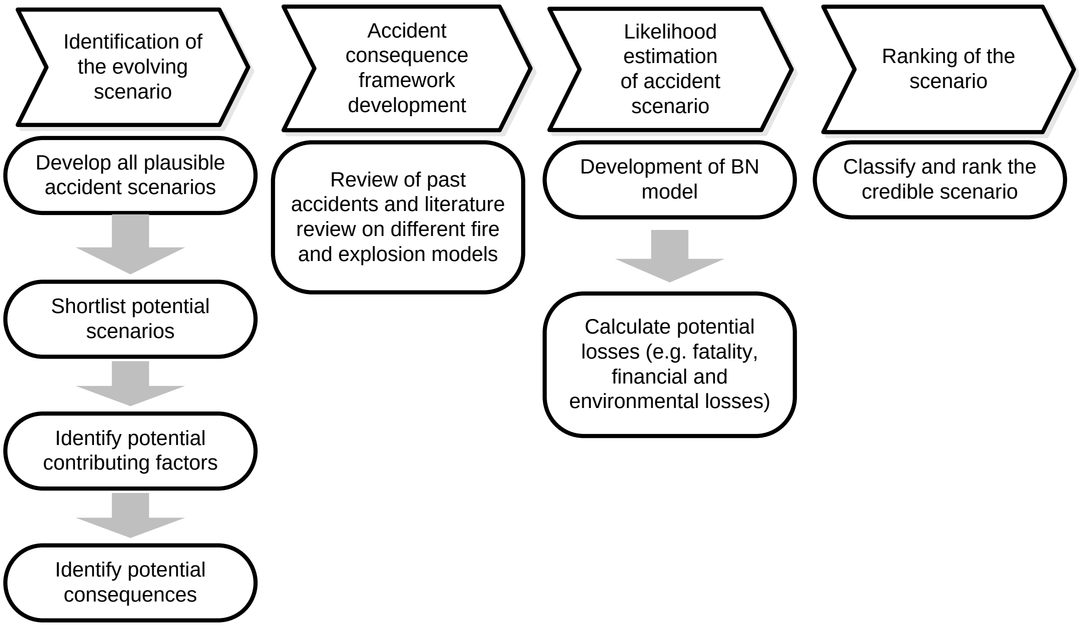


Figure 2–2: The flowchart of scenario based ranking of the most credible scenarios.

2.3.1. Evolving scenario identification

In the proposed methodology, potential fire/explosion consequences and evolving scenarios are identified through Hazard and Operability Study (HAZOP). Usually, scenarios are defined as the deviation of one or combination of different variables. After studying the potential accidents and scenarios that are developed due to deviations of relevant factors, significant consequences are identified using consequence modelling framework. Hence, all plausible accident scenarios are developed as a result of chemical, liquid or gas release. The aim is to identify and define the scenarios that may lead to fire and/or explosion.

2.3.2. Analysis of the accident

Release of hazardous material is continually initiated by a loss of containment. This may occur due to a failure of equipment (e.g., pipe leak, valve failure, and pipeline rupture). There are innumerable situations where gases, liquids, and hazardous chemicals are produced, stored, or used in a process that if released, could potentially result in a hazardous event. Hence, process accidents can be classified into three categories, viz. fire, explosion and toxic release which further can be classified into sub-categories such as fireball, flash fire, jet fire, pool fire, VCE and BLEVE. Fire can only occur when it results from the mixing of flammable gases with air or other oxidative means (Assael and Kakosimos, 2010). Release mechanism of heavy gas and dispersion from a pressurised liquefied storage is shown in Figure 2–3 which is adopted from MINERVA (2015). Type of release can be categorised into sub-categories, (1) discrete, and (2) continuous, as presented in Figure 2–4 (O&G, 2015). During process leak/release, several factors play a major role to initiate the event and assist the progression of fire and explosion consequences. After the initial release, the consequence can be different depending on released substances (e.g., liquid, gas, liquid gas and vapour) and environments such as high pressure, wind and temperature. For instance, release of a hydrocarbon may form liquid pool which is then ignited if the released material is flammable and ignition sources are available. However, presence of immediate ignition may lead to pool fire. This liquid can be evaporated and form flammable cloud, which may lead to flash fire if delayed ignition occurs. The flammable cloud can disperse depending on meteorological conditions (e.g., the wind speed) and delayed ignition possibly leads to VCE (Assael and Kakosimos, 2010; Dadashzadeh et al., 2013b; Mannan, 2012; Vinnem, 2007), which is also termed as unconfined, partly confined or confined explosion. If the released material is a mixture of two phases, gas cloud can form and continuous release with sonic speed can disperse quickly which, if ignited, may lead to jet fire (Planas and Casal, 2009). Fireball can occur due to a sudden leak and ignition of pressurised flammable gases. In any case, the final accident scenario may lead to fire, explosion, toxic release or quickly disperse into the atmosphere. Explosion can be defined as an occurrence of blast wave due to rapid release of energy (CCPS, 2010). This release of pressure can be caused by:

nuclear reactions, loss of containment in high-pressure vessels, high explosives, vapour explosions, runaway reactions, combustion of dust, mist or gas (including vapours) in air or in other oxidizers (Assael and Kakosimos, 2010). BLEVE is also another type of explosion, which occurs due to flashing of liquids when a vessel with high vapour pressure substance fails (Assael and Kakosimos, 2010; Dadashzadeh et al., 2013b).

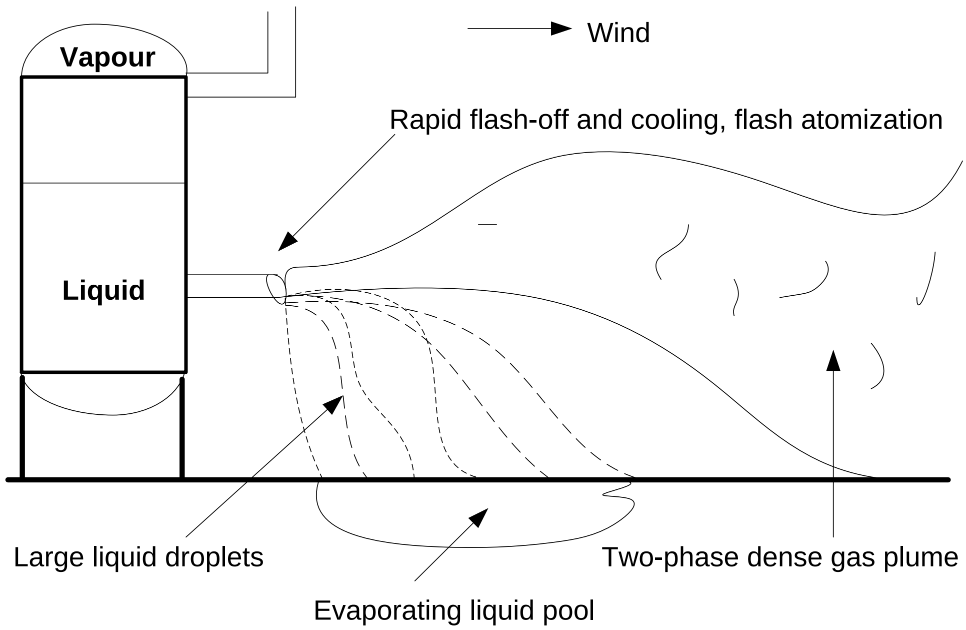


Figure 2–3: Heavy gas dispersion released from pressurized liquefied storage.

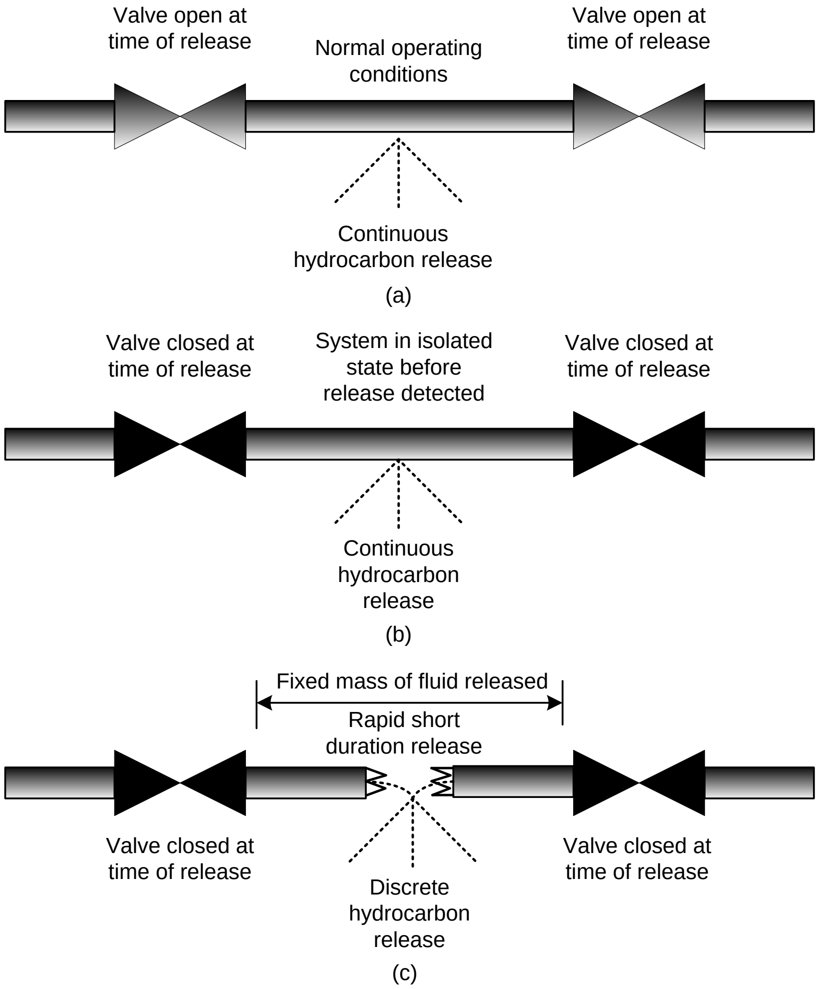


Figure 2–4: (a) Continuous release of hydrocarbon in normal operating conditions, (b) Continuous release of hydrocarbon in isolated state (fixed mass), (c) Discrete release of hydrocarbon in rapid short duration (fixed mass).

2.3.3. Accidence consequence framework development

Major process and offshore accidents can lead to evolving scenarios due to interactions among different events; for instance, fire followed by an explosion (Dadashzadeh et al., 2013b). The degree of consequences due to the accident event largely depends on type of flammable materials released, release condition, type of discharge, dispersion, ignition, area of congestion, amount of release and surrounding environment. Due to evolving characteristics of a consequence, several impact factors are studied and taken into consideration during the modelling. After reviewing and analysing historical documents (CSB, 2007; Gómez-Mares et al., 2008; Håvold, 2010; Khan et al., 2002; Kujala et al., 2009; Ventikos, 2002; Ventikos and Psaraftis, 2004; Wang et al., 2005) on fire and/or explosion consequence analysis, the author is trying to incorporate potential factors interacting in numerous consequences. The resulted framework is demonstrated in Figure 2–5.

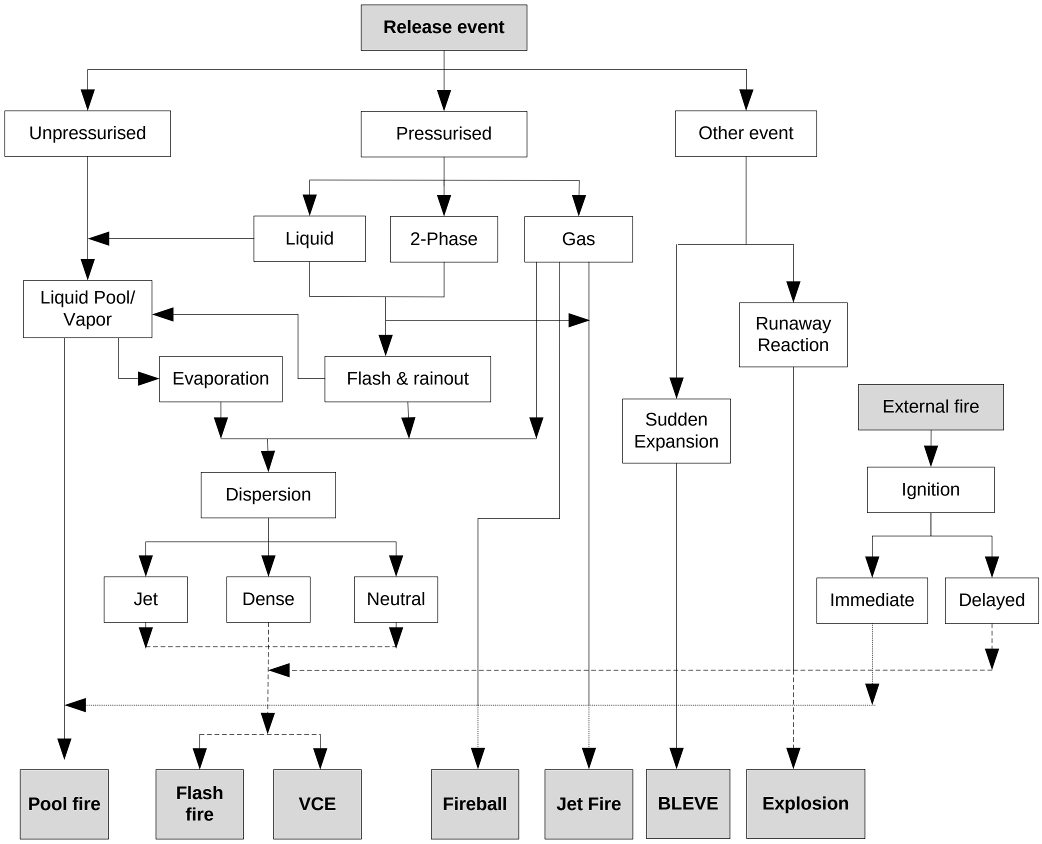


Figure 2–5: Fire and explosion consequence phenomena and their interrelationship.

2.4. Accident scenario likelihood estimation

2.4.1. Bayesian network (BN)

The BN incorporates two parts, viz. the qualitative representation that includes a graphical structure and the quantitative representation that includes the conditional probabilities (Christen et al., 1994; Korb and Nicholson, 2010; Pearl, 1988). Accidents in large-scale and complex process facilities can be modelled using BN. The BN is a widely used probabilistic graphical approach to represent accident scenario (Khakzad et al., 2011, 2013a) in marine and offshore system. The representation of the BN structure is through directed acyclic graphs (DAG) G = (V, E), where V denotes the set of nodes and E denotes the set of edges of the graph structure. Each edge is a directed link between two nodes, which represents the causal probabilistic dependence between the linked nodes. In addition, A conditional probability table (CPT) is assigned to determine the conditional dependency between the linked nodes (Jensen and Nielsen, 2007). The joint probability distribution of a set of random variables $U = \{A_1, ..., A_n\}$ based on the conditional independence and the chain rule (Pearl, 1988), included in the network as:

$$P(U) = \prod_{i=1}^{n} P(A_i \mid Pa(A_i)) \tag{2-1}$$

where $P(U)$ denotes the joint probability distribution of variables and Pa (A_i) as the parent set of variable A_i.

Bayes theorem is used in the BN to update the occurrence probability (prior) of events given new observations, called evidence E, to yield the consequence probability (posterior) using following equation:

$$P(U \mid E) = \frac{P(U,E)}{P(E)} = \frac{P(U,E)}{\sum_{U} P(U,E)} \tag{2-2}$$

In Bayes' Theorem, the knowledge of the thing before the test is called the "Prior Probability", the accuracy of the test is called the "Conditional Probability", and the final result after the test is called the "Posterior Probability". A simple BN example containing six nodes and seven arcs is presented in Figure 2–6. In this small network, the node consequence has two states, viz. S_1 and S_2 which are influenced by type of ignition, node C (e.g., quick ignition and delayed ignition), meanwhile S_1 requires a delayed ignition and S_2 requires a quick ignition (Table 2-1).

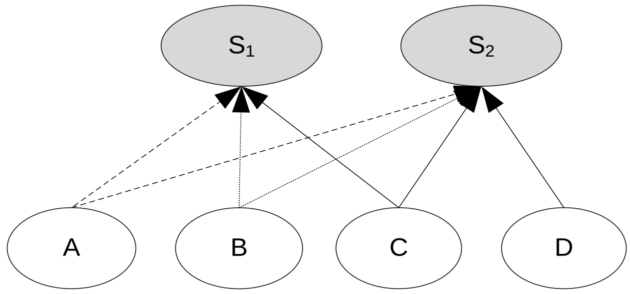


Figure 2–6: A typical BN for liquid propane release and potential consequences.

Table 2-1: Possible consequences based on primary causes in a liquid propane release.

Discharge type (A)	Discharge condition (B)	Ignition type (C)	Pool formation (D)	Consequence
Liquid	Continuous	Quick	Yes	S_2
Liquid	Continuous	Delayed	No	S_1

BNs are favoured over conventional probabilistic techniques as they offer advantages such as (1) BN can be used to model accident scenarios and determine the probabilities of different scenarios using accident prior information, (2) the dependency and conditionality of the primary causes and consequences (Jensen and Nielsen, 2007), (3) the accident information can be updated at any time using the real system data, and (4) adding a new piece of information in BN requires only a small number of directed edges in addition to small number of probabilities (Pearl, 1988).

2.4.2. Development of the BN model

In the proposed method, a method of applying BN in the consequence assessment has been suggested. The model is developed based on fire and explosion consequence framework mentioned in Figure 2-5. This figure is being translated into a BN model. After identifying all plausible hazards, the BN model is constructed to formulate possible contributing factors (e.g., release condition, type of discharge, dispersion, type of ignition and area of congestion) and accident consequences based on previous studies and expert judgement. The proposed scenario based BN model includes the following main steps; (1) Design of the consequence modelling framework, and the BN, (2) Calculation and analyses of the likelihood results using probabilistic approach (e.g., forward analysis in BN). The BN is constructed for each individual consequence (e.g., pool fire, jet fire, fireball, BLEVE, VCE and toxic release) to identify and analyse the causal factors that lead to the final events.

2.4.3. BN construction for consequences and ranking of the scenario

The BN construction begins by considering release of material or process leak including impact factors such as release condition, type of discharge, type of dispersion, type of ignition and area of congestion. Considering previous studies, ignition probability and occurrence probability of release event have taken into consideration. However, occurrence probability for other contributing factors (e.g., release condition, type of discharge, and type of dispersion) are not available and these probabilities are assigned based on expert judgement. The five experts, who have more than ten years of research and industry experience in the processing industry and are familiar with the risk and reliability, have been selected to assign the probabilities of the root causes. Release conditions refer to type of release based on accident scenarios. It consists of four states viz. (i) pressurised, (ii) unpressurised, (iii) others, and (iv) no release. Release state "others" has been kept as demonstrating sudden expansion and runaway reaction of liquid and gas. However, "no release" has been kept supporting no release option for the BN nodes viz. release conditions, discharge type, liquid pool, flash and rainout, evaporation, and dispersion. Also, "no effect" is considered in "consequences" and "credibility ranking" node. Here, "no effect" state depends on "no release". Simply, if there is no release there will be no consequences/no effect. Four types of discharge have been considered being, (i) gas, (ii) two-phase, (iii) liquid, and (iv) vapour. Two nodes viz. "Pressure build up" and "Runaway reaction" show

Boolean values “Yes” and “No” as the outcome. The nodes “Pressure build up”, “Discharge type” and “Runaway reaction” are dependent on “Release conditions”. Similarly, “Flash and rainout”, “Dispersion”, “Consequences”, and “Liquid pool” are dependent on “Discharge type”. Three types of dispersion are included in “Dispersion” node viz. jet, dense cloud and neutral. “Area of congestion” has two states being “unconfined” and “confined” area. Similarly, “Ignition” node has three different states being “Early ignition”, “Delay ignition” and “No ignition”. The “Consequences” and “Credibility ranking” node consist of nine different states viz. BLEVE, fireball, pool fire, flash fire, toxic effect, VCE, jet fire, explosion and no effect.

In the present study, a probabilistic approach (BN) is followed by a mathematical model that is integrated with accident causation factors. The evolving scenarios from release events to credibility ranking for a general release event are presented in Figure 2–7. The illustrated figure is a simplification of the conversion of fire and explosion consequence framework to BNs. A typical conditional probability table (CPT) for consequences of the proposed BN model is also presented in Table 2-2.

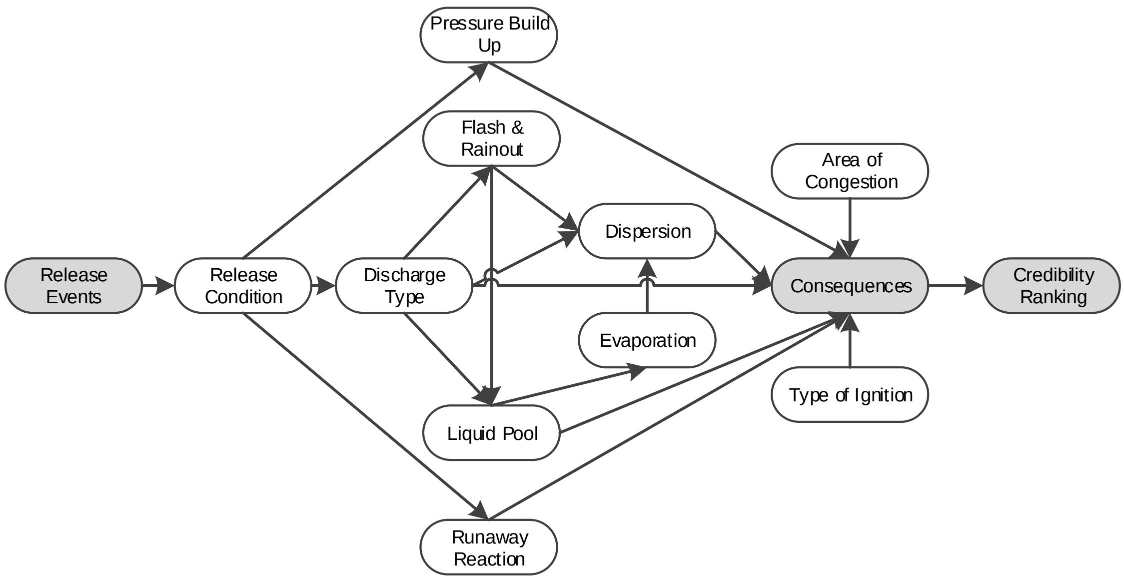


Figure 2–7: A generic BN of liquid/gas release event.

Table 2-2: A typical CPT for fire and/or explosion consequences.

Causes			Consequences			
Discharge	Dispersion	Ignition	Jet Fire	CVCE	Flash Fire	Fireball
Gas	Jet	Delay	-	-	1	-
Two phase	Jet	Delay	-	-	1	-
Liquid	Jet	Delay	-	-	1	-
Gas	Dense Cloud	Delay	-	1	-	-
Two phase	Dense Cloud	Delay	-	1	-	-
Liquid	Dense Cloud	Delay	-	1	-	-
Gas	-	Early	1	-	-	-
Two phase	-	Early	1	-	-	-
Liquid	-	Early	1	-	-	-
Gas	-	Early	-	-	-	1

2.4.4. Ranking of the accident scenario and probability estimation

The credibility ranking in this study is adopted from Khan (2001), measured on a scale of 0 to 1, and is demonstrated in Figure 2–8. The classification of credibility is distributed in three zones, viz. uncertainty, credibility and maximum credibility as explained in MCAS method. These credibility factors are demonstrated on a credibility scale where uncertainty (0-0.2) postures lowest risk, credibility (0.2-0.5) postures enough damage and maximum credibility (≥0.5) postures catastrophes. Based on primary causes and specific condition for a scenario, fire and/or explosion consequences (e.g., BLEVE, explosion, fireball, flash fire, jet fire, pool fire, and VCE) are identified. Afterwards, potential damages (e.g., fatalities, financial, and environmental loss) are estimated using MCAS method. Based on these three parameters, each specific scenario is ranked according to their priority; compared with other scenarios and further analysed to choose the most credible ones.

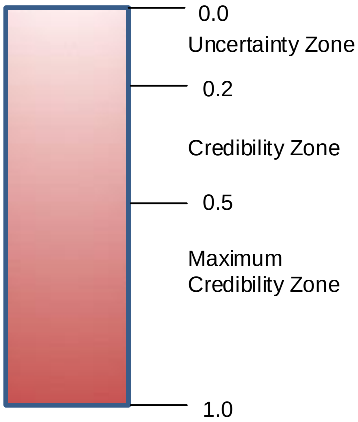


Figure 2–8: Classification of credibility in MCAS method.

2.5. Application of the methodology: case studies

In this section, the proposed model in Section 2.4.2 is demonstrated on two case studies of ammonia and LNG release in chemical and offshore process facilities. The detailed scenarios are analysed using BN as shown in Figure 2–7. The probabilities of basic events are assigned based on literature review and expert judgement.

Ammonia is a colourless gas and lighter than air. It is highly soluble in water and can be liquefied at room temperature by applying 8-10 atm pressure. Liquid ammonia can be boiled at -33.5°C under 1 atm pressure. It also freezes at a temperature of -77.8°C. Likewise, LNG is a condensed natural gas as its boiling temperature ranges from -166^{o}C to -157^{o}C at atmospheric pressure. It includes component mixture of methane, ethane, propane, nitrogen and other particles; however, these particles are combustible with a lower flammable limit (LFL) of 4-5% by volume in air and an upper flammable limit (UFL) of 15%, depending on temperature (Bernatik et al., 2011). Ammonia gas is flammable in air in the range of 16-25% by volume and can explode if released in an enclosed space with the presence of an ignition source. It is considered a high health hazard as ammonia gas can cause lung injury and the liquefied ammonia gas can cause frostbite and corrosive injury to skin and eyes (HHS, 2000). LNG in liquid form itself will not explode within storage tanks, since it is stored at approximately -256°F (-160°C) and at atmospheric pressure. If LNG is spilled on water or land, it will not mix with the water or soil, but evaporates and dissipates into the air leaving no residue. The resulting LNG vapours (methane) can be ignited with the presence of an ignition source where the concentration is above the LFL and below UFL. However, LNG release due to leakage or rupture in piping under pressurised condition can cause flash fire, pool fire, jet fire, BLEVE, fireball, explosion, asphyxiation, cryogenic burns and Rapid Phase Transformation (RPT) as mentioned by Woodward and Pitblado (2010).

2.5.1. Case study 1: Ammonia release in chemical process facility

Implementation of the developed methodology is explained using a liquefied ammonia release study to envisage the most credible accident scenarios based on primary influence factors. If liquefied ammonia is released to the atmosphere in pressurised condition, it can give rise to a two-phase discharge and the physical phenomena can be changed to liquid atomization (break-up), rainout and expansion to ambient pressure (Busini et al., 2011). It should be noted that this is a hypothetical case study to simply explain the application of the proposed methodology which is equally applicable to complex offshore processing facilities as well.

A vessel, containing 500 metric tons of liquefied ammonia at 15°C and 6.5 atm, is located in one corner of a fertilizer plant. The vessel is connected with one input line, one outflow line, a pressure-relief valve and other conventional safety devices. The population density near the plant is about 250 persons/km^2, and asset density is around \$300/m^2 near the vessel. A bird sanctuary is observed about 1,000 m away from the site. A small truck is parked about 200 m away with engine turned on. Relevant parameters considered for this study are presented in Table 2-3. The value of these parameter has been adopted from previous research (Khan and Abbasi, 1997; Khan and Abbasi, 1998a).

Table 2-3: Important parameters for the ammonia release study.

Parameters	Value
Chemical involved	Ammonia
Quantity of the chemical involved	5,00,000 kg
Phase of the chemical	Liquefied
Unit operation	Storage
Operating temperature, *T*	15°C
Operating pressure	6.5 atm
Degree of conjunction at the site	0.40
Site population density, *PD* (within region of 2000m radius)	250 persons/km^2
Asset density, *AD* (within region of 500m radius)	300 ($/m^2)
Unacceptable financial loss, *UFL*	10000 ($/yr)
Population distribution factor (*PDF*)	0.3 (dimensionless)
Weather probability factor, *WPF*	0.3 (dimensionless)
Importance factor, *IM*	1.0 (dimensionless)

Based on the information provided in the selected case study, five different accident scenarios are considered, as follows:

Scenario 1: High pressure in the vessel causes the pressure-relief valve (at the top of the vessel) to open, which leads to a continuous release of ammonia to the atmosphere until 80% of the chemical is released.

Scenario 2: Due to improper maintenance or other problems, a leak develops in the vessel’s input or output pipeline. The leaking area is believed to be 40% of the pipeline’s cross-sectional area. This scenario is modelled as continuous release of liquid ammonia near ground level causing subsequent evaporation and dispersion.

Scenario 3: High pressure develops in the vessel either due to overfilling or to a runaway reaction. The instantaneous release of high pressure causes the vessel to fail as a boiling-liquid, expanding-vapour explosion (BLEVE), and the released chemical disperses into the atmosphere.

Scenario 4: Excessively high pressure develops in the vessel beyond the design capacity of the pressure relief valve and fails instantly causing release of a large amount of dense gas. The instantaneously released chemical disperses into the atmosphere and ignition source causes VCE.

Scenario 5: Ammonia is released from the joints, causing a pool of liquid to form. The released chemical subsequently evaporates into the atmosphere and disperses.

The summary of the case study result is presented in Table 2-4.

Table 2-4: Credibility factors for the scenarios in the ammonia release.

Scenario	Damage Radius, m	Frequency of Occurrence /per year	Outcome	Fire and Explosion				Toxic Release		
				Financial loss	*Fatalities*	*Environmental loss*	L_1	*Fatalities*	*Environmental loss*	L_2
1	2500	5.0E-05	Toxic event	-	-	-	-	1.00	0.98	1.00
2	1100	4.0E-04	Toxic event	-	-	-	-	1.00	1.0	1.00
3	250*	7.0E-05	BLEVE	0.41	0.10	0.01	0.47			
	1270							0.79	0.35	0.86
4	350†	1.0E-06	VCE	0.00	0.00	0.00	0.00	0.01	0.00	0.01
	1200									
5	950	8.0E-05	Toxic event	-	-	-	-	0.51	0.22	0.61

*Damage radius for BLEVE
†Damage radius for VCE

The credible values presented in Table 2-4 are calculated following MCAS method where L_1 stands for credibility of fire and explosion and L_2 stands for credibility of toxic release.

$$L_1 = [1-(1-\text{Financial loss})(1-\text{Fatalities})(1-\text{Environmental loss})] \qquad (2\text{-}3)$$

$$L_2 = [1-(1-\text{Fatalities})(1-\text{Environmental loss})] \tag{2-4}$$

After analysing the selected accident scenarios from above release, potential consequences such as BLEVE, VCE and toxic release are identified. All relevant data are extracted from the selected accident scenario based on scenario assessment. The simulation result of Figure 2–7 is shown in Figure 2–9. In the BN, primary causes and consequences due to ammonia release are drawn through causal arcs. The BNs in this study are assessed using the software GeNIe 2.1 (BayesFusion, 2017). In scenario 1, it is clear that pressurised liquefied ammonia release has occurred. Due to a pressurised release, leaking ammonia gives rise to a two-phase discharge. After the two-phase release, flash and rainout, liquid pool and evaporation may occur due to ambient conditions. As a result, jet, dense cloud or no dispersion may occur in the release scenario. Since the release area is unconfined and no ignition source is present, there is a chance of toxic effect in the accident scenario. In case of scenario 2 and 5, almost same phenomena have occurred as scenario 1. In scenario 3, a BLEVE has occurred due to increasing pressure inside the vessel. The likelihood of a BLEVE, P (Consequence = *BLEVE*) is calculated based on available condition (i.e. Release event = *yes*, Release conditions = *Others*, Pressure build up = *yes*, Runaway reaction = *no*, Area of congestion = *unconfined* and Type of ignition = *early*). On the contrary, backward or diagnosis analysis can find the most probable causes for the occurrence of BLEVE. For example, with all probabilities remaining the same for the BN, the consequence of a BLEVE can be selected as 100% which in turn shows the contribution of all precursor values in the network. It is evident from the network that despite any evidence on type of congestion and type of ignition, there is 48% chance of a BLEVE and almost 2% chance of an explosion (not shown in the figures). If only pressure builds-up inside the vessel and no runaway reaction occurs, the chance of a BLEVE is still 48%. However, if early ignition is selected as evidence despite type of congestion, the chance of a BLEVE is increased to 50% (not shown in the figures). If it is unconfined area and early ignition is selected as evidence, then the chance of a BLEVE is about 100% (Figure 2–9). In scenario 4, VCE has occurred due to high pressure and delayed ignition. Due to a pressurised release, flash and rainout or liquid pool may occur. A dense cloud of released gas is dispersed to a nearby ignition source and causes VCE. For above cases, fatalities, financial, and the environmental loss are estimated using MCAS method. Due to a BLEVE, financial loss has been observed to 0.41, fatalities to 0.1 and environmental loss to 0.01 (

Table 2-4). Using these values in Eqs. (2-3) and (2-4), final credible value for a BLEVE has been estimated to 0.47 which is in credible region. A higher fatalities and environmental loss are observed due to a toxic release in scenario 1 and 2. However, a higher degree of financial loss is also observed in scenario 3 due to a BLEVE. In terms of fire and explosion, scenario 3 is the most credible. In terms of toxic release, scenario 1, 2 and 3 are the most credible. Overall, scenario 3 is the most credible in terms of combined effect of fire and explosion and toxic release.

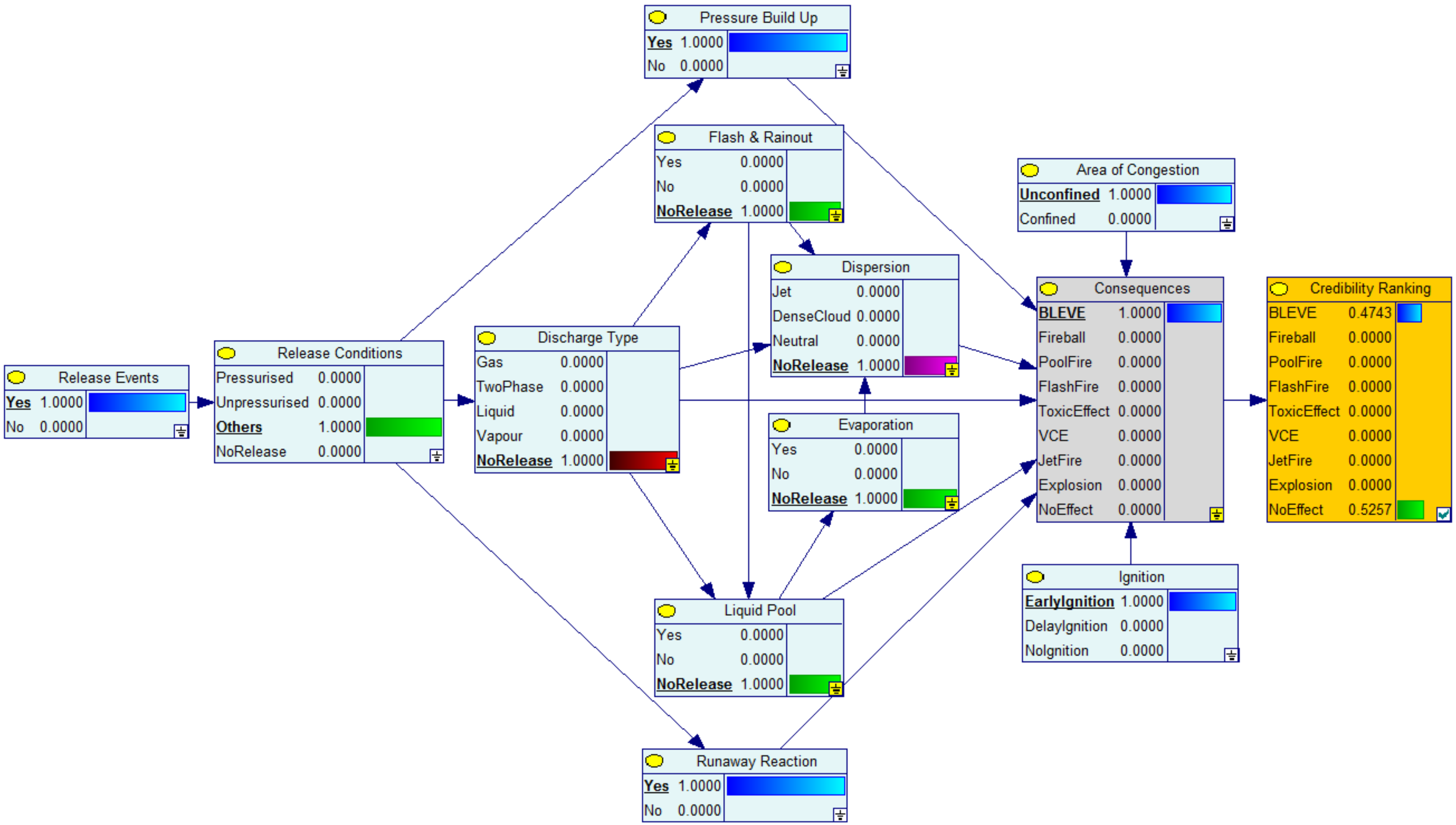


Figure 2–9: BN simulation result for ammonia release study of scenario 3 (BLEVE).

2.5.2. Case study 2: LNG release in FLNG facility

In this case study, four different accident scenarios that are likely to occur during the FLNG offloading mechanism are considered. LNG vapours are non-toxic; however, accidental release of LNG can be deviated to evolving scenarios ranging from a destructive VCE to pool fire with successive explosion of its contents. The FLNG facility may pose mostly fire and explosion hazards.

On a bright sunny day, 20,000 kg of LNG is stored at an extremely cold temperature (-162º C) in a double-walled tank at 25 kPa (3.6 psi) on Prelude FLNG. The floating platform is about 488 m long and 74 m wide. The wind speed is 3 m/s with an ambient temperature of 25°C. The tank is connected by a pipe (10-inch diameter, control valve and other conventional safety devices) to offloading system. The facility is near an offloading vessel surrounded by water. There are about 230 people working in both FLNG facility and offloading vessel. Asset density around the floating unit is 276916 ($/m^2). There is a marine ecosystem surrounded by water. Relevant parameters considered for this study are presented in Table 2-5.

Table 2-5: Important parameters for the LNG release study.

Parameters	Value
Hydrocarbon	LNG
Quantity of the released hydrocarbon	20000 kg
Phase of the hydrocarbon	Liquefied
Unit operation	Processing facility
Operating temperature, *T*	-162°C
Operating pressure	25 kPa
Degree of conjunction at the site	0.40
Site population density, *PD* (within region of 500m radius)	6.40E-03 persons/m^2
Asset density, *AD* (within region of 500m radius)	276916 ($/m^2)
Unacceptable financial loss, *UFL*	1.00E06 ($/yr)
Unacceptable damage area, UDA	1000 (m^2/yr)
Population distribution factor (*PDF*)	0.3 (dimensionless)
Weather probability factor, *WPF*	0.3 (dimensionless)
Importance factor, *IM*	1.0 (dimensionless)

Based on the information provided in the selected case study, four different accident scenarios are considered, as follows:

Scenario 1: LNG is released from the connected pipe, causing a pool of liquid to form. The released hydrocarbon subsequently evaporates into the atmosphere and disperses.

Scenario 2: An instantaneous release of LNG leads to liquid pools evaporating to form a flammable vapour plume. After a quick dispersion, at 60s, delayed ignition occurs in the area, which leads to a destructive VCE in the process.

Scenario 3: LNG liquid escapes from the double walled tank due to a crack in supply line, forming vapour cloud, which is then pushed, downwind toward the engine room, where it likely ignites, and jet fire is formed.

Scenario 4: Pipelines disconnected from offloading vessels and fall into water causing a continuous release of LNG on surface water initiating subsequent wave and RPT.

The summary of the above case study result is presented in Table 2-6.

Table 2-6: Credibility factors for the scenarios in the LNG release.

Scenario	Damage Radius, m	Frequency of Occurrence /per year	Outcome	Fire and Explosion			Credibility
				Financial loss	*Fatalities*	*Environmental loss*	L_1
1	450	2.80E-05	Vapour	-	-	-	-
2	300*	2.60E-06	Pool fire	0.20	0.14	7.35E-04	0.31
	450†		VCE	0.46	0.31	1.65E-03	0.63
3	400‡	6.50E-07	Jet fire	0.09	0.06	3.26E-04	0.14
4	200	2.90E-10	RPT	-	-	-	-

*Damage radius for Pool fire
†Damage radius for VCE
‡Damage radius for Jet fire

The credible values presented in Table 2-6 are calculated following Eq. (2-3) stated in the MCAS method. After studying the selected accident scenario, fire and explosion consequences such as pool fire, jet fire, and VCE are identified. Following the shortlisted accident scenarios, hypothetical values are assigned as the prior probabilities of primary causes in the BN. The BNs in this study are also assessed using the software GeNIe and the output for scenario 2 of the developed BN is presented in Figure 2–10. In scenario 1 of the case study, unpressurised release of LNG occurs. The released vapour forms a liquid pool and disperses into the atmosphere as soon as it evaporates. In above scenario, fire and explosion events have not occurred due to absence of ignition. In case of scenario 2, unpressurised release of LNG forms a liquid pool and ignites in presence of early ignition. The resulting vapour disperses, and delayed ignition contributes in destructive VCE. The likelihood of pool fire with observed data, P (Consequence = *Pool Fire*) is calculated based on available condition (i.e., Release event = *yes*, Release conditions = *unpressurised*, Discharge type = *Vapour*, Liquid pool = *yes*, Area of congestion = *unconfined* and Type of ignition = *early*). It is evident from the network that due to quick ignition the chance of pool fire is about 100% according to the calculation results of the BN. In the proposed BN, backward analysis presents the most probable causes for the occurrence of pool fire. Despite any evidence on type of congestion and type of ignition, there is 3% chance of pool fire (not shown in figures). However, if early ignition is selected as evidence despite type of congestion, the chance of pool fire is increased to 50%. Due to an early ignition and unconfined released area, the chance of pool fire is about 100%. The resulting liquid pool may evaporate and disperse as dense cloud of vapour which ignites if delayed ignition occurs. The chance of VCE is about 33% due to contribution of dense cloud, confined space and delayed ignition. From the calculation for importance degree of probability, it can be observed that the effects of some specific primary causes (e.g., release condition, discharge, liquid pool, dispersion, area of congestion and type of ignition) on the probability of pool fire are higher compare to other primary causes. In scenario 3, a pressurised release of LNG has occurred. The resulting gas cloud is ignited in engine room through an ignition source and jet fire has occurred. In case of scenario 4, continuous release of LNG into surface water causes rapid phase transformation (RPT) which may result in minor explosion. Using the MCAS method, fatalities, financial, and the environmental loss are estimated for above scenarios. Due to pool fire, financial loss has been observed to 0.20, fatalities to 0.14 and environmental loss to 7.35E-04. These values are used in Eqs. (2-3) to calculate final credible value of pool fire. The final credible value of pool fire is estimated to 0.31 which is in the credible region. In case of VCE, financial loss has been observed to 0.46, fatalities to 0.31 and environmental loss to 1.65E-03. Final credible value due to VCE has been estimated to 0.63 which is in the maximum credible region. In case of jet fire, final credible has been estimated to 0.14 which is in uncertain region. In above cases, a higher degree of financial loss and fatalities are observed in scenario 2 although minor environmental losses are observed in scenarios 2 and 3. Overall, scenario 2 is the most credible in terms of fire and explosion.

Figure 2-11 demonstrates the effects of primary causes on fire and/or explosion consequences (case study 2). Figure 2-11 (a-c) clearly shows the effects of release condition, type of discharge and type of dispersion on individual fire/explosion consequences. From the figure, it is clear that unpressurised condition has more effect on pool fire compare to VCE and jet fire. In terms of discharged material, liquid has similar effect on both VCE and jet fire. However, pool fire is highly influenced by vapour. Effect of dispersion on pool fire, VCE and jet fire is demonstrated in Figure-2-11 (c). From the figure, it is clear that dense cloud has more effect on VCE. Credibility of pool fire, VCE and jet fire is presented in Figure 2-11 (d) where VCE ranks the top in terms of damages.

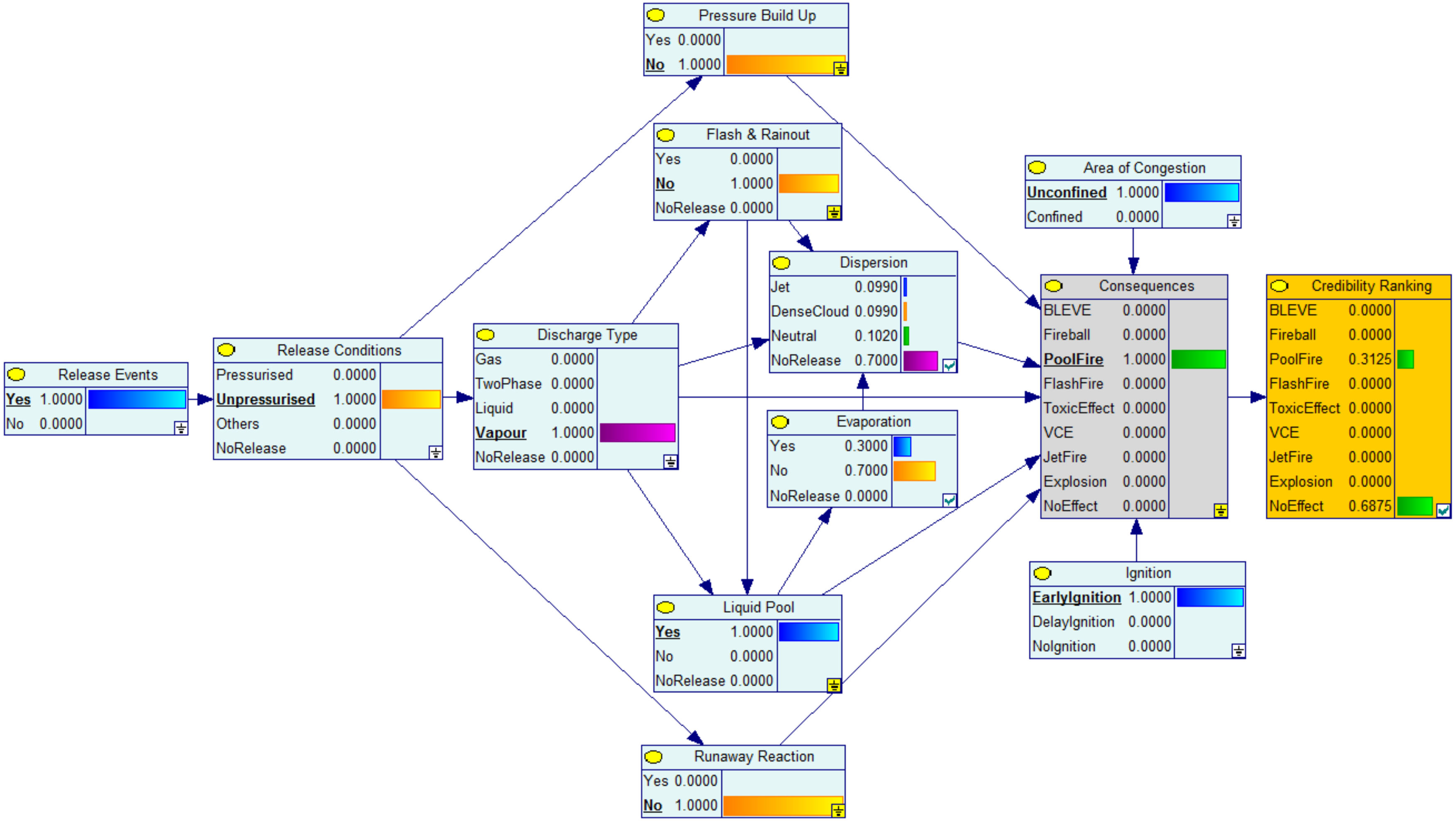
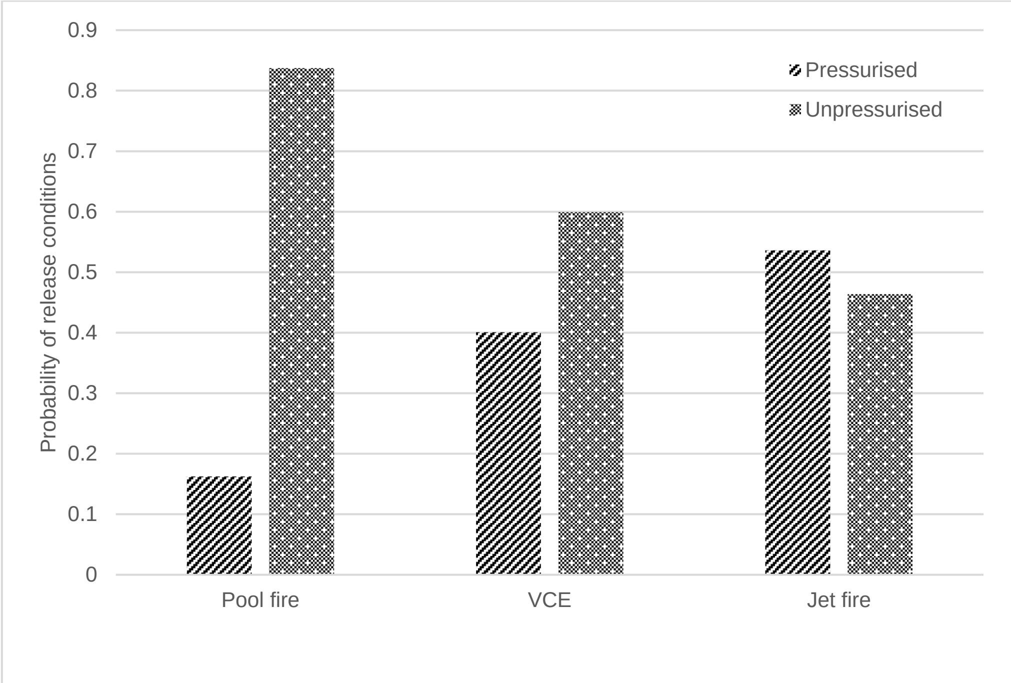
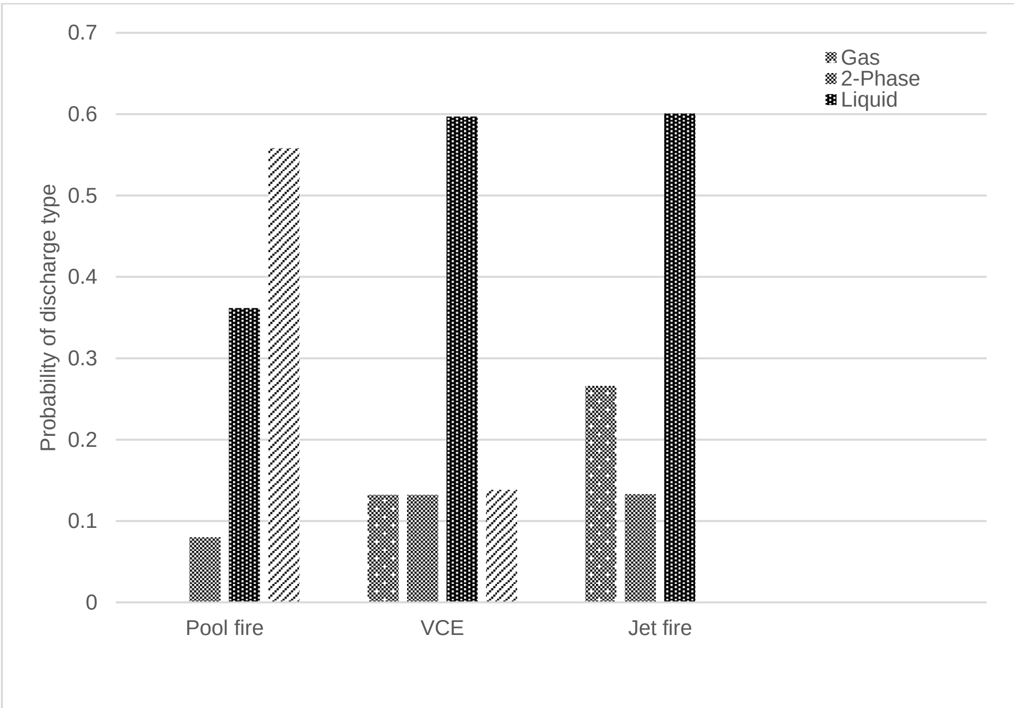


Figure 2–10: BN simulation result for LNG release study of scenario 2 (pool fire).



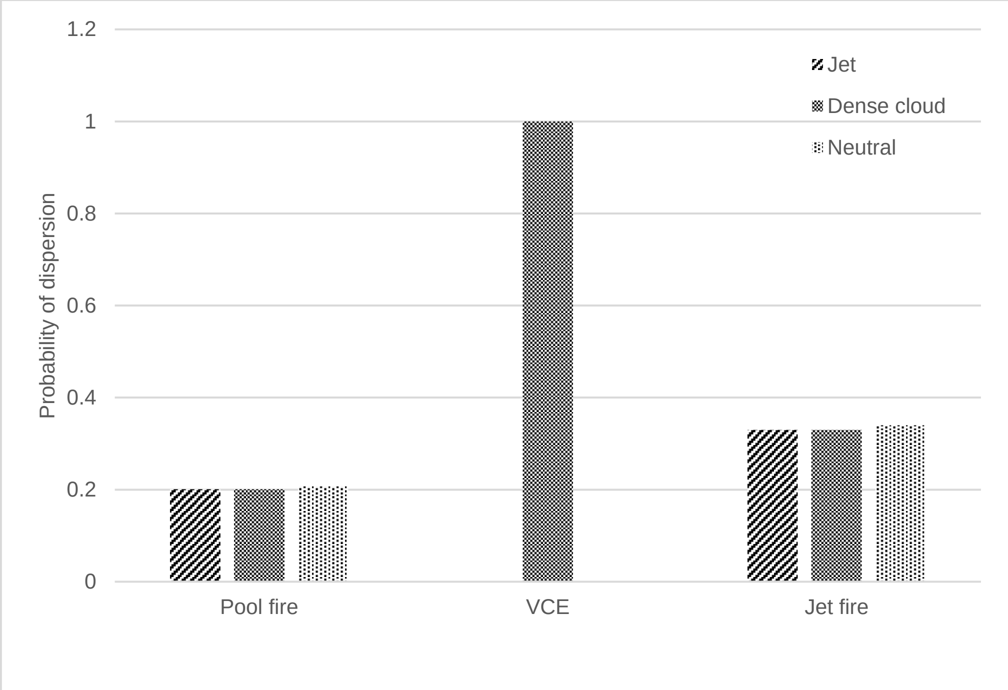
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Probability of release conditions
Pressurised
Unpressurised
Pool fire
VCE
Jet fire

(a)

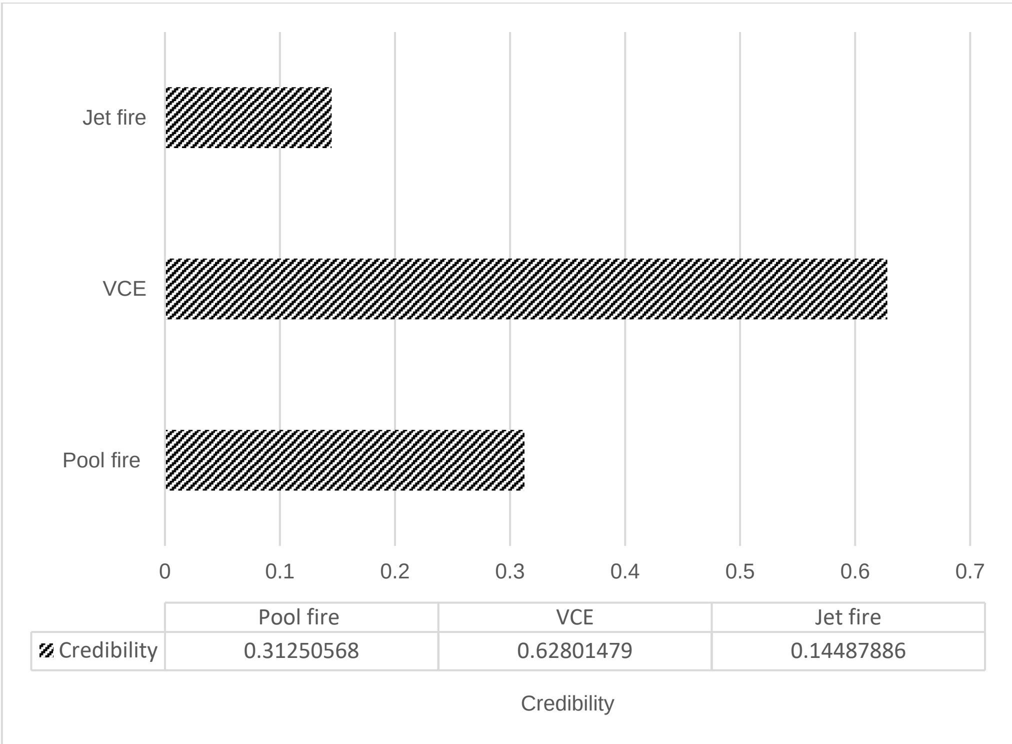


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Probability of discharge type
Gas
2-Phase
Liquid
Pool fire
VCE
Jet fire

(b)



(c)



(d)

Figure 2–11: Probability of primary causes (a) release conditions, (b) type of discharge, and (c) dispersion for different consequences of pool fire, VCE and jet fire, and (d) credibility of pool fire, VCE and jet fire.

2.6. Conclusion

In this article, a network-based approach is proposed to envisage the most probable accident scenarios in complex offshore process facilities. A review of existing scenario-based modelling approaches reveals few limitations in modelling of accident scenarios such as consequence analysis of individual fire and explosion ignoring the complex scenarios. It is evident that the majority of existing models focus on individual accident modelling approach. However, in real life, accident events can evolve through various consequences. In a process accident, more or less potential damages can cause fatalities, financial loss as well as environmental damages. Besides damages, it is necessary to identify a probable accident event, magnitude of damages and its impact on the environment to estimate and envisage prospective loss. Hence, identification and ranking of potential damages are needed to ensure maximum safety. To identify potential causes and consequences in a process accident scenario, a consequence modelling framework is developed based on previous literature review. A BN is developed to model evolving scenarios and credibility. The proposed methodology is applicable for modelling probable evolving scenarios, evaluating their occurrences and ranking most probable scenarios by applying case specific data. The application of the proposed model has been demonstrated on two specific case studies, viz. ammonia and LNG release on process facility. The causes and consequences of ammonia and LNG release event are investigated through BN method and further assessed though MCAS method to validate the model. The methodology developed in this study using BN is effective in determining the most credible accident scenario in offshore process industries due to evolving scenarios generated from fire, explosion and toxic release. Using MCAS method, fatalities, financial and environmental losses are estimated for each scenario. Further, these values are used to calculate final credible values for each scenario which is incorporated in the network. In the present study, the proposed model is combining potential consequences in a unique specific model. By taking advantage of BN, conditional dependency has been illustrated between the primary causation factors and the consequences through direct causal arcs. The posterior likelihood of accident consequences has been estimated using prior data. In addition, the prior probability has been updated considering the evidence of specific consequences. The proposed concept model is applicable to the marine and offshore process facility; however, with further modification it can be applied to other process facilities including aviation and traffic accident for analysing possible consequences.

Acknowledgements

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Chapter 3: Marine transportation risk assessment using Bayesian network: application to Arctic waters

The work presented in this chapter has been submitted for review in *Ocean Engineering*. The paper has been edited for inclusion into this thesis to improve readability. The citation for this research article is:

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Abstract

Maritime transportation poses risks regarding possible accidents resulting in damage to vessels, crew members and to the ecosystem. The safe navigation of ships, especially in the Arctic waters, is a growing concern to maritime authorities. This study proposes a new risk model applicable to the Northern Sea Route (NSR) to investigate the possibility of marine accidents such as collision, foundering and grounding. The model is developed using Bayesian Network (BN). The proposed risk model has considered different operational and environmental factors that affect shipping operations. Historical data and expert judgments are used to estimate the base value (prior values) of various operational and environmental factors. The application of the model is demonstrated through a case study of an oil-tanker navigating the NSR. The case study confirms the highest collision, foundering and grounding probabilities in the East Siberian Sea. However, foundering probabilities are very low in all five regions. By running uncertainty and sensitivity analyses of the model, a significant change in the

likelihood of the occurrence of accidental events is identified. The model suggests ice effect as a dominant factor in accident causation. The case study illustrates the priority of the model in investigating the operational risk of accidents. The estimated risk provides early warning to take appropriate preventive and mitigative measures to enhance the overall safety of shipping operations.

3.1. Introduction

The vast seaborne trade has permitted an enormous variety of resources to be widely accessible around the world and has thus helped accelerate the world economy. More than 90% of global trade is carried out via sea routes (IMO, 2012) as it is cost-effective. The Northern transport corridor, known as the Northern Sea Route (NSR) in the Arctic region, is one of the potential trade routes connecting major Asian and European ports. The opening of the NSR has reduced shipping distances and fuel consumption as well as emissions (Kitagawa, 2008). According to Schøyen and Bråthen (2011), the distance between a Northwest-European port and the Far East is reduced approximately 40% by using the NSR as an alternative route compared to the traditional route through the Suez Canal.

The presence of sea ice, extremely low temperatures and drifting icebergs has made this region mostly inaccessible for marine transportation and poses threats to mariners and the current ship technologies (Ellis and Brigham, 2009). As the size and number of ships have increased significantly over time (Toffoli et al., 2005), the possibility of shipping accidents in this region is expected to grow (Balto, 2014; Borgerson, 2008). Previous studies confirm that increasing traffic of oil tankers in the Barents Sea will result in a significant number of accidents if further maritime safety measures are not attained (NME, 2011).

A combination of accidental events and processes are recognised as the leading contributors to ship accidents (Yang et al., 2013). Human error and visibility issues are identified as significant contributors to vessel collisions (Fowler and Sørgård, 2000; Khan et al., 2017; Macrae, 2009; Merrick et al., 2000; Van Dorp et al., 2001; Zhang and Thai, 2016). Additionally, human fatigue, lack of technical knowledge of ship systems, poor communication, faulty policies, practices and standards, are significant human and organisational related issues facing the maritime industry (Dhillon, 2007; Talley, 2002).

The safe navigation of ships, especially in the Arctic waters, is of ultimate concern for researchers as well as maritime authorities. Risk assessment on maritime transportation and risk reduction measures are a part of ongoing studies. However, limited research has been conducted on the effect of both cold and harsh environmental conditions on shipping accidents in this region. This paper proposes a new risk model applicable to the NSR considering the particular environmental and operational conditions to quantify the risk of transit on Arctic routes.

3.1.1. Literature review regarding existing accident models

In maritime risk and consequence assessment, several methods have been applied to estimate the causation probability. Among the ship accidents, collision has been the focus of many related studies in recent years. Fujii and Shiobara (1971) introduced one of the most common approaches to estimate the number of ship collisions, where the number of collisions is calculated as a product of the number of geometrical collision candidates and a causation probability. Macduff (1974) initially proposed a ship collision and grounding modelling based on available historical accident records. However, it lacked a clear understanding of accident causes. Risk analysis tools such as fault trees are developed to estimate the causation probability of collision event (Pedersen, 1995; Rosqvist et al., 2002). Marine Accident Risk Calculation System (MARCS) is also developed based on fault tree analysis while considering major shipping accidents such as collisions, powered grounding, drift grounding, foundering and fire and explosions by Fowler and Sørgård (2000). Danish institution COWI (2008) proposed formal safety assessment (FSA) methodology for sea traffic taking into account collisions and groundings. Martins and Maturana (2010) applied fault tree analysis to assess the collision and grounding probability using FSA method. Zaman et al. (2014) estimated the risk of collision in the Malacca Strait using the FSA approach. Merrick et al. (2000) developed a Probabilistic Risk Assessment (PRA) technique considering expert judgment to assess the accident risk in the Prince William Sound. Van Dorp et al. (2001) developed maritime accident event chain which included collision, grounding and fire/explosion using the available data combining with expert judgment. Montewka et al. (2010) proposed a geometrical model to assess the likelihood of ship collisions. A collision probability model based on Monte Carlo simulation technique was developed by Goerlandt and Kujala (2011). Later, it was used in evaluating the risk of tanker collisions in the Gulf of Finland (Goerlandt et al., 2011). A probabilistic approach was proposed to assess the risk and sustainability associated with ship collision by Dong and Frangopol (2014). Goerlandt et al. (2015) developed a ship collision alert system to measure ship collision risk based on fuzzy approach and expert elicitation. Banda et al. (2015) visualised the accident risks through a hazard identification model in the Finnish-Swedish winter navigation system. Sormunen et al. (2015) investigated chemical tanker collision as a case study by taking into account data uncertainties. Montewka et al. (2014) proposed BN framework for ship-ship collisions in the open sea, evaluated the probabilities of these events and finally, determined the severity of a collision. Goerlandt and Montewka (2015) developed a Bayesian network model and applied it to a case study of the oil spill from a tanker to quantify the risk. Mazaheri et al. (2016) proposed an evidence-based and expert-supported Bayesian Belief Networks (BBNs) for assessing the probability of ship-grounding accidents. Fu et al. (2016) developed a causal probabilistic model to predict the probability of a ship stuck in ice in the Arctic waters using the BBNs. In this causal model, a set of input parameters such as hydro-meteorological conditions (air temperature, ice concentration, ice thickness, sea temperature, wave height and wind speed) along the analysed route were considered. Khan et al. (2017) proposed an Object-Oriented Bayesian Network (OOBN) model to predict ship-ice collision probability considering navigational, operating and human factors.

3.1.2. Discussion on existing accident models

Most of the studies discussed above focused on a single accident (Dong and Frangopol, 2014; Fu et al., 2016; Fujii and Shiobara, 1971; Goerlandt and Kujala, 2011; Goerlandt and Montewka, 2015; Khan et al., 2017; Mazaheri et al., 2016; Montewka et al., 2014; Montewka et al., 2010; Pedersen, 1995; Rosqvist et al., 2002; Sormunen et al., 2015; Zaman et al., 2014) or combined ship accidents (Banda et al., 2015; COWI, 2008; Fowler and Sørgård, 2000; Macduff, 1974; Martins and Maturana, 2010; Merrick et al., 2000; Van Dorp et al., 2001) and modelling (individual or integrated) of different types of accidents in maritime traffic. However, integrated accident models based on different types of accidents for the NSR are quite limited. Recorded data of wave height and wind speed for the NSR are never considered in the literature or accident analysis. Thus, conventional ship accident models developed for Arctic regions may not address the integrated accident events such as ice-ship collision, foundering and grounding, simultaneously considering recorded data of five sea states. The conventional risk analysis approaches are commonly adopted to identify the propagation of primary causes that may lead to the potential accident consequences. In the quantitative risk analysis, fault tree is used to estimate the probabilities of possible causes of an event and event tree is used to model potential consequences of that event (Meel and Seider, 2006). Additionally, fault trees may be used to find the logical relationship between the primary causes and the potential consequences. However, in this study, BNs are favoured over fault tree analysis due to advantages such as conditional dependency between primary causes and consequences, common cause issues between the linked nodes, the addition of new accident prior probability as well as updating the real-time posterior probability in the model. The advantage of the integrated method is its capability to predict the particular accident considering the environmental and operational factors. This helps to define the accident according to the existing conditions and to take the appropriate mitigative measures to decrease the consequences in advance which enhances overall reliability of the shipping operations.

In reality, it is possible to have an ice-ship or ship-ship collision which may lead to a ship sinking. Ship stuck in ice may lead to damage to the ship's hull and result in a capsizing accident. However, in the proposed model latter impact of collision or grounding is not considered, with only the causes behind the collision, foundering and grounding and the individual accident probabilities considered. The aim is to show the likelihood of each accident considering most possible causes. It is possible to connect arcs between accident events and show further impact due to those accidents.

The present study aims to develop a novel methodology by using the BN to represent different potential accident scenarios considering the particular environmental and operational conditions to quantify the risk of transit on Arctic routes. Using BNs, the probabilities of three possible accident types on Arctic routes are quantified based on primary causes and their associated probabilities. The methodology relies on historical data and expert judgments in the estimation of the probability distributions of primary events. The primary objective is to reduce the risk of environmental damage to a minimal level caused by ship collisions, while continuously striving to further reduce the risk. Three different accident scenarios that are likely to occur during Arctic transit are studied. A case study which exemplifies the application of the developed methodology is also presented.

3.2. Bayesian networks

A BN is a specific type of graphical model that is represented as a directed acyclic graph where the nodes represent random variables and directed arcs imply local conditional dependencies between parent and child nodes (Ghahramani, 1998; Jensen and Nielsen, 2007; Mihajlovic and Petkovic, 2001; Neapolitan, 2003; Pearl, 1988). In BN, the network structure, the graph, can be observed as a qualitative part of the model, whereas the probability parameters add a quantitative extent to the model (Darwiche, 2009). The joint probability distribution of a set of random variables $U = \{A_1, ..., A_n\}$ based on the conditional independence and the chain rule (Pearl, 1988), is included in the network as:

$$P(U) = \prod_{i=1}^{n} P(A_i \mid Pa(A_i)) \tag{3-1}$$

where $P(U)$ denotes the joint probability distribution of variables and Pa (A_i) as the parent set of variable A_i. Accordingly, the probability of A_i is calculated as:

$$P(A_i) = \sum_{U \setminus A_i} P(U) \tag{3-2}$$

where the summation is taken over all the variables except A_i. A simple BN with a set of dependent random variables A_i is illustrated in Figure 3–1 and the corresponding joint probability distribution as: $P(A_1, A_2, A_3) = P(A_1) \times P(A_2 \mid A_1) \times P(A_3 \mid A_1, A_2)$.

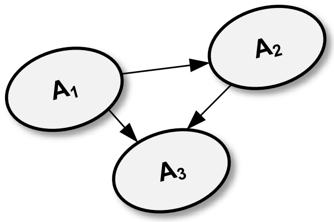

Figure 3–1: A typical Bayesian network representing A_1 as root node; A_2 as intermediate node; and A_3 as leaf node.

Bayes theorem is used in the BN to update the occurrence probability (prior) of events given new observations, called evidence *E*, to yield the consequence probability (posterior) using the following equation:

$$P(U \mid E) = \frac{P(U, E)}{P(E)} = \frac{P(U, E)}{\sum_{U} P(U, E)} \tag{3-3}$$

BNs are favoured over conventional probabilistic techniques as they offer advantages such as (i) BN can be used to model accident scenarios and determine the probabilities of different scenarios using accident prior information; (ii) BN considers the dependency and conditionality of the primary causes and consequences (Jensen and Nielsen, 2007); (iii) the accident information can be updated at any time using the real system data, and (iv) adding a new piece of information in BN requires only a small number of directed edges in addition to a small number of probabilities (Pearl, 1988). BN is a promising method for risk analysis of large and complex systems due to its flexible structure and probabilistic reasoning engine (Khakzad et al., 2013b). For example, Hänninen and Kujala (2012) evaluated the ship-ship collision causation model which consists of 100 nodes and 179 links. The application of BN to quantitative risk analysis of offshore drilling operations and marine and offshore accident analysis has previously been discussed by researchers (Baksh et al., 2017; Baksh et al., 2015; Baksh et al., 2016; Hänninen and Kujala, 2012; Khan et al., 2017; Li et al., 2012; Mazaheri et al., 2016; Montewka et al., 2014; Zhang and Thai, 2016; Zhang et al., 2016). BN model is established based on unwanted events by addressing potential primary causes leading to the unwanted events (ship collision, foundering and grounding in this study), and exploring the possible consequences resulting from the unwanted event.

3.3. Proposed methodology for ship accidents in harsh environments

In this study, a BN reasoning process has been developed to provide a natural framework for maritime risk analysis in Arctic transit. A flowchart of the proposed approach is shown in Figure 3–2 to ensure a step-by-step systematic process. The entire methodology consists of four steps. GeNIe is used as the robust BN programming environment for the risk modelling and its probability calculations.

A brief explanation of each step of the modelling process is given in the following paragraphs.

Step 1: This step heavily relies on historical data and subject-matter experts (SMEs) judgments from the potential sources, such as databases, tests, experiments, simulations, networks and analytical models (Fowler and Sørgård, 2000; Fujii and Shiobara, 1971; Macduff, 1974; Tabri et al., 2009). Any observed data that is available from a specific scenario can be used to update or refine the estimates of previous accident data. In this way, uncertainties and limitations can be reduced in respect of new data or SMEs judgement.

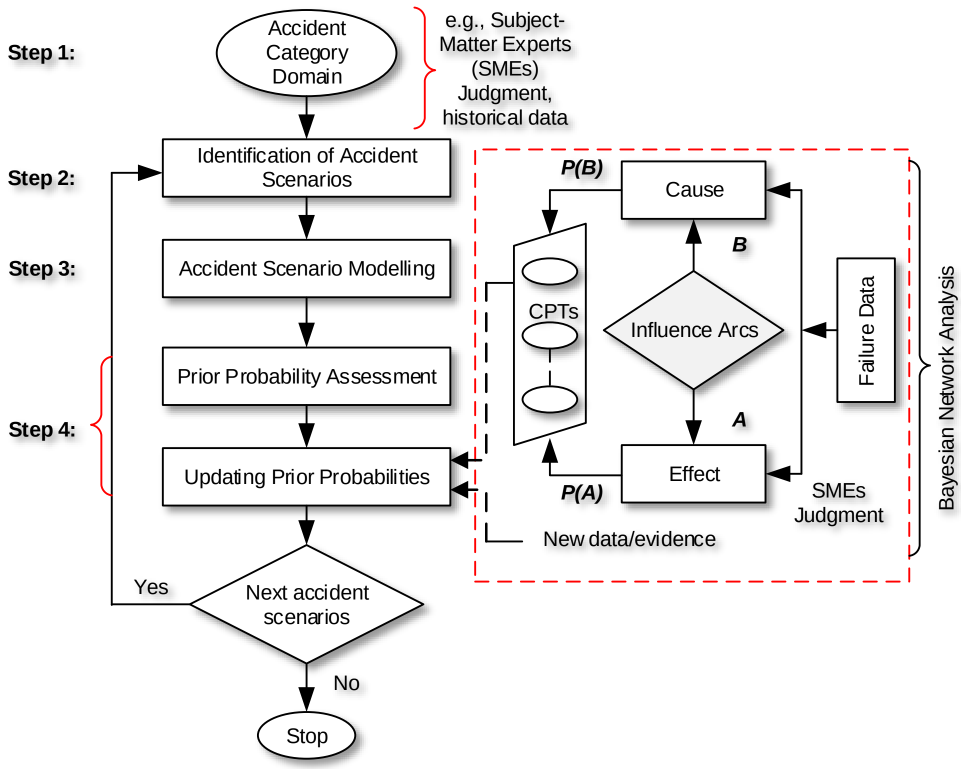

Figure 3–2: Developed risk-based methodology for risk analysis in Arctic transit.

Step 2: In this step of the process, the potential accident scenarios (e.g., the collision of a ship with Arctic ice during Arctic transits has been taken into consideration) and associated consequences (foundering and grounding) that can occur in a harsh environment are identified. For example, grounding may occur due to a failure of any of the sub-events (e.g., harsh weather effect, the faults of vessels, navigation failures, visibility issues and tug assistance failure). Further, sub-events such as the fault of the vessel itself can be defined as anchor failure, loss of power in the danger area, or loss of propulsion of the vessel.

Step 3: In this step in constructing the BN, the graphical representation is crucial as it indicates the relevant variables (nodes) and dependencies (arcs). It helps to determine the level of detail that needs to be used in subsequent models. Also, it provides the reasoning for analysing and communicating causal assumptions, which is not easy to express using standard mathematical notation (Pearl, 2000). For example, if there are two events A and B (A as a cause event and B as an effect event), these two events can be labelled and mapped into the network. An arc can be placed between an influencing node (parent) and an influenced node (child) to determine influence relationships between these nodes (Eleye-Datubo et al., 2006). The terminating arrow of the arcs can be set to point to the child nodes.

Step 4: In this step, a set of input parameters based on environmental and operational conditions are assigned. The BN is used to show the causal relationship between the linked nodes. The Bayesian inference consists of computing the conditional probabilities with the BN; that is, to specify the states for each child node and input values for parent nodes in a conditional probability table (CPT). Prior evidence can be entered into the model by manually setting probabilities in the network. The Bayesian inference is enabled via the Bayes formula. Once the prior information is provided in the directed graph, the entered evidence propagates in both directions. The updating belief is computed after prior evidence is entered to improve the prior knowledge, and thus the prior probability values, are updated by calculating posterior probabilities. At any part of the analysis, if it is required to see the contribution of different factors in the causation of an accident, backward analysis can be considered. Regarding newly available data, the calculated posterior probabilities can be considered as the new prior probabilities for future risk assessment. BN simulation software GeNIe is used to estimate the posterior probabilities as well as updating the prior knowledge.

3.3.1. Accident probability analysis: scenario-based modelling

In this accident scenario modelling, the collision of a ship with Arctic ice during Arctic transits has been taken into consideration. The characteristics of Arctic transits and environments are different and unique compared to local waterways. Therefore, particular factors might have a significant influence on the risk associated with marine navigation in the Arctic waters, such as pack ice effect, environmental obstacles, the combined effect of wind and wave, and emergency assistance. However, detailed investigations of Arctic routes are out of the scope of the present study. Most vessels sailing through the NSR will require icebreaker escort (ABS, 2014). In this accident scenario, it is anticipated that an icebreaker escorts a ship by making channels in the ice. Icebreaker escort is required when the vessel's capability to navigate or manoeuvre is severely restricted by existing ice conditions. There are two main methods of escorting in ice – leading and towing. In both cases the escorted vessel follows the ice channel made by the escorting icebreaker or icebreakers. The failure of the icebreaker to remove ice may affect ship navigation which can result in an ice-ship collision. Furthermore, the risk of collision between the vessel and icebreaker needs to be considered, particularly if the icebreaker comes to a sudden stop and should not hesitate to decrease speed or stop at immediate notice. As the traffic on the NSR may increase in future decades, another marine vessel's fault can be considered in ship-to-ship collision scenarios.

Different consequences can take place regarding a ship collision. If it is an oil tanker, the breach in the vessel's hull can propagate a massive spill of hydrocarbons into the sea with the impact being significant damage to the marine environment, economic losses as well as a costly recovering process (Dave and Ghaly, 2011; Goerlandt et al., 2012b). The release of hydrocarbons may subsequently lead to different credible accidents such as vapour cloud explosion (VCE) and pool fire (Assael and Kakosimos, 2010; Baksh et al., 2017; Baksh et al., 2016; CCPS, 1994; Crowl, 2010). The consequences are inevitable and may cause many fatalities and the loss of the entire vessel if the release of hydrocarbons and fire cannot be controlled and extinguished promptly (Dave and Ghaly, 2011). In harsh and cold environments, emergency responses and evacuation procedures are always challenging for rescue vessels and the crews as they may be delayed due to maneuvering through ice-covered waters (Verny and Grigentin, 2009). These factors may also lead to severe consequences on Arctic routes and need to be considered in the consequent analysis of ship accidents. Due to the potential consequences caused by the cold and harsh environment, it is vital to identify the future risk of ship collision with regards to the increase in ship traffic in this region (Balto, 2014). The geographical map of the northern transport corridor in the Arctic region is taken from the Arctic portal (Arctic-Portal, 2017) with the route through five seas drawn with a dotted line as illustrated in Figure 3–3.

Figure 3–3: The northern transport corridor with ice and water.

3.3.2. Dynamic ice-ship collision modelling on the NSR

Dynamic risk assessment method takes advantage of case scenario data and updating mechanisms to reassess the risk regarding new information (Khakzad et al., 2012). In Bayesian updating approach, new data are employed in the form of likelihood functions to update prior probabilities using Bayes' theorem (Kalantarnia et al., 2009; Kanes et al., 2017; Kelly, 2011; Meel and Seider, 2006). In this present work, a dynamic risk-based model is developed to analyse shipping accidents on the NSR and reduce the risk of accidents. The model is capable of updating the results whenever new evidence is available during the operation. Although the time slice is not considered within the model, the observations (e.g., new data) however, can be a function of time.

The proposed model will estimate the collision, foundering and grounding probability considering harsh environmental conditions and would be suitable for Arctic region transits. In the proposed model, a ship collision with ice in the Arctic region plays a central role. However, it is recognised that accident type, such as ship foundering and grounding, also has the potential to take place. Therefore, while the development of ship collision model is in progress, two other accident types, viz. foundering and grounding are also taken into consideration. A digital chart error leads the USS Guardian to misplace the actual location of a reef by about eight nautical miles and resulted in grounding on that reef in the Philippines (Couttie, 2013). However, no evidence has been found of ship grounding due to digital chart error in the Arctic region. This factor is considered due to the USS Guardian tragedy. Quantitative risk analysis of a ship accident requires historical data or expert judgment. In case of missing or limited historical data (to estimate the probabilities of events), the expert judgment is considered (Lindhe et al., 2009). SMEs judgement is utilised where no data are available for a particular type of accident nor the causes of that accident.

In the developed model, three random variables represent ship accidents, such as collision, foundering and grounding. Ship collision is directly/indirectly influenced by twenty primary nodes and twelve intermediate nodes. Similarly, foundering and grounding of a ship are also influenced by seventeen and twenty-two primary nodes, respectively. These primary nodes are used as input information for the intermediate nodes where given probable causes for ship accident, the likelihood of a collision, foundering and grounding, are modelled.

The impact of sea wave height, wind speed and pack ice effect are highly seasonal, affecting both navigation and ship transit. This effect can differ in summer or winter. In winter, icebreakers prepare the narrow channels in Arctic transit which helps the ship to navigate and hence icebreakers impact on ship collision frequency. In the developed model, twelve wave states (e.g., S_{wv1}, S_{wv2}, S_{wv3}…, and S_{wv12}) are considered which define the wave heights between 0-2 m and are which are profoundly influenced by the wind. For the wind, the first eleven states (e.g., S_{wd1}, S_{wd2}, S_{wd3}…, and S_{wd11}) are considered to be between 0-28 m/s as per Beaufort scale. For example, in the summer season, if the wind speed is in state 6 (8.0-10.7 m/s) which is considered as a fresh breeze, the wave height can be in any state (S_{wv1} – S_{wv12}) for that season. Similarly, during winter (December to February) the NSR can be frozen, and therefore high waves on the sea are very unusual. The BMT ARGOSS UK provided the recorded data for different wave height (H_s) and wind state (u_{10}, 10 m above sea level) for the period

January 1979 to December 2015 at 3-hourly time intervals (BMT-ARGOSS, 1979-2015).

Different wind speed and pack ice together can make for dangerous icing conditions. However, in comparison to sea wave height and wind speed, icing condition may require a longer time to change from its original state. According to the Meteorological Institute, icing from sea spray will occur at temperatures below -2°C and with wind speeds more than 11 m/s. Due to the slower formation of sea spray icing and rare, changing conditions, different types of pack ice such as very close pack ice, close pack ice, open pack ice and very open pack ice, respectively can be observed (OCIMF, 2014). The detailed characteristics of the sea ice types have been discussed by previous researchers (Balto, 2014; Bourke and Garrett, 1987; Kum and Sahin, 2015; OCIMF, 2014; Thelma, 2010; Zakrzewski, 1986).

In this study, BNs are used to synthesise expert judgment and recorded data obtained from previous research to perform the integrated analysis. The BN is constructed by primary and intermediate nodes with connected arcs. These nodes have two states only, each with some probability. For instance, “Ice-breakers failure” can be “Yes” or “No”, and the probability of the “Yes” or “No” can be determined by historical statistical data. The intermediate nodes are affected by associated primary causes. For instance, the intermediate node “Visibility issues” can be affected by the node “Human factor failure”, “Radar failure”, and “Environmental obstacles”. Here, “Human factor failure” consists of a variety of sub-groups of errors, which can be the intended or unintended action of a human. These sub-groups are defined as human performance influencing factors (PIFs) (HSE, 2017). For example, interpretation failure, fatigue/sleeplessness, and/or alcohol abuse can be combined with a human factor failure (Uğurlu et al., 2015). On the otherhand, human error is considered as an action or decision which was unintended (HSE, 2017). It should be noted that both of these factors are considered as human errors in many available literatures. However, to differentiate these factors in the developed BN, human error is considered as a single action on failure to detect ice and iceberg using conventional marine radars and thermal imaging cameras while navigating on the NSR. However, considering all the PIFs would make the accident modelling network complex enough to show the general applicability for mariners. Rather, integrating too many sub-factors (contributors to the accidents) into the main factor, the human error and the human factor are considered in the proposed model. Taking advantage of the BN, an unwanted event (e.g., collision, foundering, or grounding) is defined and then decomposed to determine its environmental and operational events. The developed BNs for ship collision, foundering, and grounding accident scenarios are illustrated in section 3.4.2.

3.4. Application of the methodology: case study

The application of the proposed method is applied to a case study of a ship collision, navigating on the NSR, to estimate the accident probability. The extreme temperature, pack ice, and multi-year sea ice effect and severe climate changes are some of the drawbacks of this region (Kassens, 1994; Melling, 2002; OCIMF, 2014; Thelma, 2010; US-Navy, 1988; Zakrzewski, 1986). These areas are entirely covered with ice during winter and partly covered in summer. According to Johannessen et al. (1997), the presence of multi-year ice on the NSR creates a dangerous environment for marine operations, which subsequently necessitates a more comprehensive method and study to investigate navigational risk and challenges in the harsh and cold environments through the NSR. In the following sections, the application of the proposed methodology is applied to a case study of a ship collision navigating through the NSR.

3.4.1. The NSR economic viabilities and the associated risk

The Soviet Union developed the NSR shipping route as a major national waterway which has a history of 1306 voyages completed by 331 vessels in 1987 (Ellis and Brigham, 2009). In recent years, the Arctic Ocean has become the dominant hotspot due to its natural resources, shorter navigational routes and pirate free zone. Fossil fuel is a major attraction in Europe to manage the increasing demand for energy. A combined initiative between the NSR and the European explorer is undergoing the extraction of fossil fuel in the Barents Sea, the Kara Sea and the Yamal Peninsula (Pastusiak, 2016; Peresypkin and Yakovlev, 2008). Another growing interest in the eastern region of the NSR for East Asian countries such as Japan and China is the transport of fossil fuel to meet its energy demand (Pastusiak, 2016). An experimental voyage between Yokohama and Kirkenes in 1995 proved the NSR to be a cost-effective route compared to the Suez and Panama Canals shortening the travel time by 15 days and reducing transportation costs by up to $500,000 (Pastusiak, 2016). The NSR would connect the ports of North Asia (Japan, South Korea, and China) and north-western Europe (Hamburg, Bremen, and Rotterdam) and shorten the journey length by about 2500 nautical miles (Verny and Grigentin, 2009). After opening a new container terminal for Europe and Asia, cargo shipping increased on the NSR after 2010, exceeding 3.87 million tonnes of cargo in 2012 and expecting a future increase to more than 5.0 million tons by 2019 (Lammers, 2010; Pastusiak, 2016; Polovinkin and Fomichev, 2012). According to the Arctic Marine Shipping Assessment (AMSA) 2009 report, the estimated volume of oil and gas transportation on the NSR is expected to be about 40 million tons per year by 2020 (Ellis and Brigham, 2009). More economic aspects of Arctic transportation can be found in the literature (Ellis and Brigham, 2009; Hong, 2012; Lasserre and Pelletier, 2011; Pastusiak, 2016).

The NSR consists of the ship sailing routes between the Bering Strait in the east and the Barents Sea in the west (Johannessen et al., 2007). It connects north-western Europe and north-eastern Asia and is considered the shortest sailing route. The NSR is divided into five regions identified as the Chukchi Sea, East Siberian Sea, Laptev Sea, Kara Sea, and the Barents Sea. According to a 50-year series of data from polar stations in these regions and visual observations in open sea areas, it has been observed that ice formation begins in late August in the northern East Siberian Sea whereas, young ice formation starts in the first ten days of September north of the Kara and Laptev Seas (Johannessen et al., 2007). According to Johannessen et al. (2007), young ice appears at the end of the second 10 days of September north of the Chukchi and the Barents Seas. Zakharov (1997) presents an estimate of the average ice area in the NSR regions during March and September as described in Table 3-1. On average within 35-40 days, the Laptev and East Siberian Seas are entirely covered by young ice whereas it takes about 80-85 days for the Kara and Chukchi Seas (Johannessen et al., 2007). The Chukchi Sea has an area of 6.20E05 km^2 with an average depth of 80 m and is considered as the only route from the Pacific to the Arctic. According to Table 3-1, an average area of 5.95E-01 million km^2 of the Chukchi Sea is ice covered in March and 1.96E-01 million km^2 in September.

Table 3-1: Average ice area (million km^2) in the marginal seas of the NSR regions during the period of the seasonal maximum (March) and minimum (September) (Zakharov, 1997).

Sea	March (million km^2)	September (million km^2)	Seasonal Changes (%)
Chukchi	5.95E-01	1.96E-01	67
East Siberian	7.70E-01	5.16E-01	33
Kara	8.30E-01	2.66E-01	68
Laptev	5.36E-01	1.96E-01	63
Barents	8.55E-01	1.28E-01	85

According to Anderson et al. (2011), the East Siberian Sea has a surface area of 8.95E05 km^2 with a mean depth of 52 m which is the shallowest amongst the seas on the NSR. Harsh environment, remote areas, and unexplored maritime areas are some of the characteristics of this region that create challenges for navigational purposes (Münchow et al., 1999). During the winter season, the mean temperature is -30^{o}C (Mulherin et al., 1994) and the entire area is ice-covered. However, during summer, 50% of the ice remains. According to the AMSA 2009 report, the entire coastal region along the eastern NSR becomes shallow for all marine operations due to the average depth of the Chukchi Sea and East Siberian Sea (Ellis and Brigham, 2009). The Laptev Sea has an area of 6.50E05 km^2. The average wind speed above the sea surface water is 5 m/s, and storms occur in the sea, three to four times a month. Also, fog is frequent in this region, and the humidity varies between 95-98% (Fofonova, 2012). The Kara Sea has the second highest surface area of 8.80E05 km^2 along the NSR with a mean depth of 110 m (Galimov et al., 2006). The Barents Sea has the smallest surface area of 1.40E06 km^2 with a mean depth of 230 m (Sakshaug, 1997; Smedsrud et al., 2010). The winter is considered to be December to February in the Barents Sea when sea ice is relatively thin compared to other regions of the Arctic Ocean. According to a report by Thelma (2010), in extreme conditions, spray and mist can build up four centimetres of ice per hour on the surface of a device in the Northern Barents Sea. The summer season provides an excellent opportunity for marine transportation as the entire Barents Sea becomes ice-free (Sakshaug, 1997).

Maritime transportation poses risks regarding possible accidents resulting in loss of life and ship's cargo as well as detrimental impacts on the marine environment. The accidents on the NSR are comparatively lower than some other regions. The AMSA 2009 report highlighted incidents and accidents which occurred in the Arctic region between 1995-2004. According to the report, 293 vessels of different categories were engaged in several accidents including 22 collisions, 68 groundings and 54 damages to the vessel (Ellis and Brigham, 2009). Marine Accident Investigation Branch (MAIB) recorded 65 incidents/accidents between 1993 and 2011 in the Arctic region (Kum and Sahin, 2015). However, only four collisions and four groundings were reported to the MAIB compared to 22 collisions and 68 groundings (Kum and Sahin, 2015). According to Safety and Shipping Review 2014, there were about seven casualties (groundings) in the Arctic region (Review, 2014). Another safety and shipping review in 2016 reported 71 shipping incidents in the Arctic waters during 2015 (Review, 2016). Growing traffic in the Arctic region may increase the risk of ship operations.

3.4.2. Accident scenario analysis

The cold and harsh environmental conditions have made the Arctic waters mostly inaccessible as a shipping route. Various factors that can affect the ship's navigation, as well as human performance in emergency situations such as wave height, wind speed, sea current, surrounding temperature harsh weather effect, and different level of ice along the NSR route, are taken into consideration. However, there are some variations between the values of the environmental factors being identified. Until today, no particular factors have been considered to divide the NSR into different regions. Hence, this route is divided based on the five different seas, the Chukchi Sea, East Siberian Sea, Laptev Sea, the Kara Sea and the Barents Sea respectively.

In this accident scenario analysis, the collision, foundering and grounding probabilities of an oil tanker and the primary causes of these consequences are adopted from previous literature (Antão and Soares, 2006; EMSA, 2009; Noroozi et al., 2014; Trucco et al., 2008; Uğurlu et al., 2015; Yeo et al., 2016) on ship accident modelling in normal conditions. SMEs are being considered if the probability of primary causes specific to Arctic environments is not available.

The severe climate in Arctic regions requires experts to re-evaluate the previous ship accident scenarios when defining the probabilities of the primary causes in this study. The five experts who have more than ten years of research and industry experience in shipping operations (on deck) and are familiar with the Arctic routes environment have been selected to assign the probabilities of the root causes. These experts were male and aged between 35 and 65 (the average age being 51.6). All the experts have their Bachelor (BSc), and Master (MSc) degrees in maritime-related fields. Two experts were working as a master, two as chief-officer, and one as second-officer in Canadian Transport Agency with little or no knowledge of assessment of probabilities. All experts were Canadian and spoke fluent English. These experts were engaged in defining the probability distributions of primary events for each region. The average is the arithmetic mean value for the primary events. The corresponding mean values of probabilities for each primary event for each specific region on the NSR are presented in Table 3-2.

Table 3-2: Mean value of probabilities for primary causes of ship collision, foundering and grounding received from historical data and SMEs judgement.

	Basic events	Chukchi Sea	East Siberian Sea	Laptev Sea	Kara Sea	Barents Sea	Data source
Index	Event	Region 1	Region 2	Region 3	Region 4	Region 5	
X1	Human factor failure	2.97E-04	3.50E-03	1.30E-03	4.00E-04	3.00E-04	SME
X2	Radar failure	2.04E-04	4.00E-04	2.00E-04	5.30E-04	3.50E-04	SME
X3	Environmental obstacles	4.33E-04	2.30E-04	1.90E-04	3.50E-04	2.90E-04	SME
X4	Mechanical failure	6.71E-05	6.00E-05	5.50E-05	5.00E-05	5.50E-05	SME
X5	Operational failure	2.54E-05	3.54E-05	2.14E-05	2.11E-05	2.90E-05	SME
X6	Contaminated fuel in bunker tanks	3.00E-05	2.10E-05	1.30E-05	1.90E-05	1.30E-05	SME
X7	Contaminated fuel measuring system fail	3.30E-05	5.30E-05	4.10E-05	3.10E-05	4.30E-05	SME
X8	Engine fails to operate	2.04E-04	3.00E-04	2.34E-04	5.30E-04	3.30E-04	SME
X9	Basic failure of the propeller	2.03E-04	2.30E-04	3.00E-04	4.03E-04	3.00E-04	SME
X10	Power failure	3.50E-04	5.00E-04	4.10E-04	3.30E-04	4.50E-03	SME
X11	Back-up power failure	1.54E-04	1.74E-04	1.59E-04	1.74E-04	1.66E-04	SME
X12	Map location not updated	1.04E-04	5.30E-04	2.11E-04	3.00E-05	1.01E-04	SME
X13	Digital chart error	3.52E-04	3.30E-04	3.00E-04	5.30E-04	4.00E-04	SME
X14	Navigator malfunction	4.48E-05	4.00E-05	3.50E-05	7.00E-05	3.00E-05	SME
X15	Inappropriate route selection	1.62E-04	3.30E-04	2.00E-04	2.09E-04	3.00E-04	SME
X16	Procedure failure	2.66E-04	1.35E-04	4.00E-04	3.00E-04	3.30E-04	SME
X17	Wind speed	See Table 3.6	See Table 3.6	See Table 3.6	See Table 3.6	See Table 3.6	(BMT-ARGOSS)
X18	Wave height	See Table 3.7	See Table 3.7	See Table 3.7	See Table 3.7	See Table 3.7	(BMT-ARGOSS)
X19	Pack ice	5.30E-03	3.00E-03	3.70E-03	1.00E-03	1.00E-04	SME
X20	Human error	1.60E-03	3.50E-03	1.30E-03	4.00E-04	3.00E-04	SME
X21	Ridge ice and iceberg	3.00E-04	5.00E-04	3.00E-04	5.00E-04	1.00E-04	SME
X22	Non-detected multi-layer ice	5.10E-04	3.00E-04	5.00E-04	4.00E-04	3.00E-04	SME
X23	Fault of other vessels	3.00E-05	5.00E-05	1.00E-05	5.00E-05	1.00E-05	SME
X24	Ice-breakers failure	2.23E-05	7.30E-04	5.30E-04	2.00E-04	1.30E-04	SME
X25	Insufficient tugboat use	2.09E-04	2.34E-04	3.30E-04	2.30E-04	1.01E-04	SME
X26	Faulty tugboat manoeuvre	6.71E-05	1.35E-04	3.50E-04	3.00E-04	2.31E-04	SME
X27	Not tight enough	6.50E-04	7.00E-04	6.90E-04	6.10E-04	7.00E-04	SME
X28	Structural failure	5.50E-04	6.00E-04	6.00E-04	5.10E-04	5.50E-04	SME
X29	Waterline reaches door	3.33E-04	4.33E-04	4.13E-04	4.03E-04	4.00E-04	SME
X30	Inadequate pumping	4.30E-05	4.90E-05	5.30E-05	5.10E-05	4.99E-05	SME
X31	Leaking	5.50E-04	4.00E-04	5.50E-04	5.00E-04	4.60E-04	SME
X32	Communication failure	6.50E-04	7.00E-04	6.10E-04	6.50E-04	6.90E-04	SME
X33	Faulty design	9.00E-04	1.30E-04	1.10E-04	9.90E-04	1.10E-04	SME
X34	Excessive wear	4.50E-04	6.00E-04	5.70E-04	5.10E-04	5.50E-04	SME
X35	Metal failure	6.00E-04	4.50E-04	5.50E-04	5.10E-04	4.90E-04	SME
X36	Cargo shift failure	4.13E-04	4.03E-04	4.33E-04	4.00E-04	4.11E-04	SME

In this study, most of the input data for the BN analysis in each particular region is received from experts. Based on the prior event probabilities assigned by the SMEs, human error effect on the detection failure is recognised as one of the recurrent causal factors for marine ship collision. Previous research suggests that about 74% or more of such accidents involve human error related factors (Rothblum et al., 2002). The cold temperature in a freezing environment can challenge the mariners which in turn may affect surveillance, reaction times, awareness and memory recall, and physical strength (Enander, 1987; Hoffman, 2002; HSE, 2017; Khan et al., 2017; Macrae, 2009; Musharraf et al., 2013; Noroozi et al., 2014). Vessel's collision with pack ice and non-detected ice is also considered as another significant factor by the experts in developing the model.

The present study is based on sea wave measurements from the NSR. The measurements were obtained from BMT ARGOSS UK. In BMT ARGOSS, global wind and wave hindcast dataset are available on a grid of spatial resolution 0.5^{o} by 0.5^{o}. The wind and wave parameters were recorded at each grid point, at 3-hourly time intervals, for the period January 1979 to December 2015. The recorded data provided by BMT ARGOSS UK consists of significant wave height, H_s (m), zero crossing wave period, T_z (s) and wind speed measured at 10 m above the surface. A sample of recorded data is shown in Table 3-3.

Table 3-3: Sample recorded data of wave parameters from the Barents Sea.

Dataset	H_s (m)	T_z (s)	U_{10} (m/s)
1	0.0024	2.8807	1.410116968
2	0.0032	2.8610	0.811585809
3	0.0047	2.8408	0.944581146
4	0.0051	1.7879	2.463794632
5	0.0064	1.8343	2.696691548
6	0.0065	1.8362	2.723586755
..	..	..	..
..	..	..	..
105127	11.3459	11.2784	19.34842017
105128	11.8528	11.3321	19.15760045

A wave is defined as the fraction of a record between two successive zero up crossings (MHL, 2016). In practice, a zero up crossing wave period is considered to occur when the surface passes through the mean line in an upward direction (Tann, 1976). It is the portion of the record between adjacent zero up-crossings. Its height, H is equal to the vertical distance between the highest and lowest point of the wave. Zero crossing wave presented in Figure 3–4 is adapted from MHL (2016). Wave data are usually collected for approx. 20 minutes on each 3rd or 6th hours assuming stable sea states (Skjong et al., 1995). Wave data can be obtained by visual observations from lighthouses, merchant ships and weather ships, however, instrumental observations can be used such as wave buoys, radars, shipborne wave recorders (SBWR), lasers, satellites and surface-piercing instruments (Skjong et al., 1995; Wang et al., 2015a). According to the World Meteorological Organization, (WMO, 1983), wave data accuracy requirements are:

± 20% for significant wave height and ± 1.0s for the average wave period.

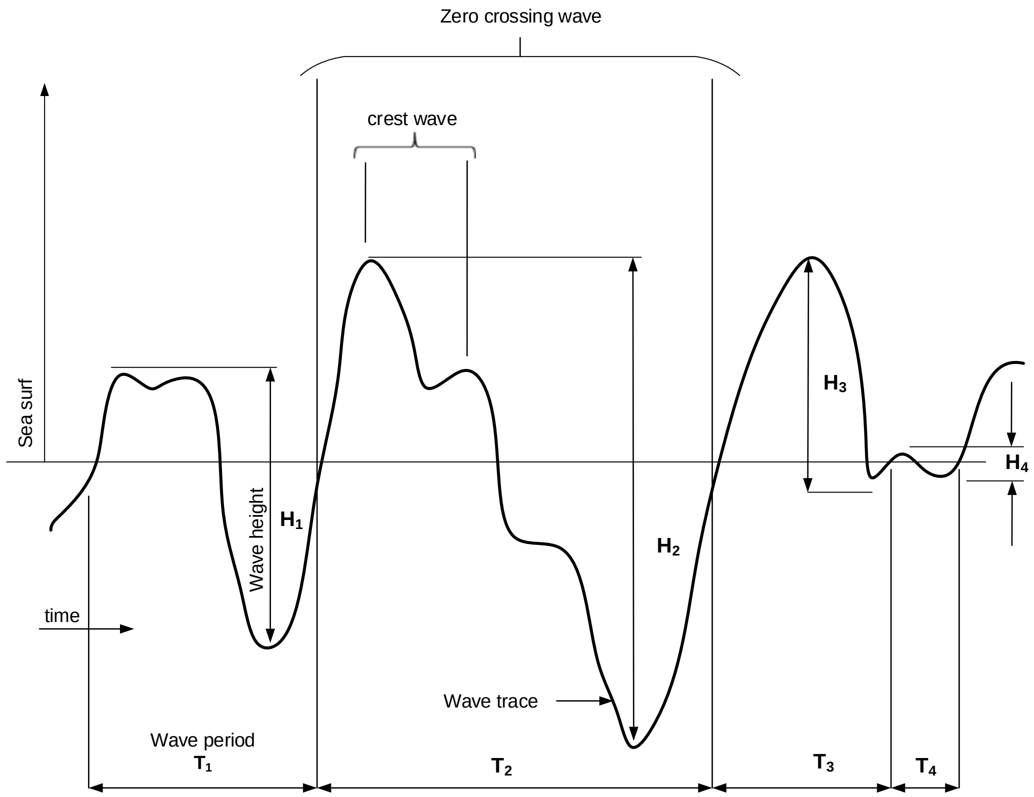

Figure 3–4: Zero crossing wave period.

According to Tann (1976), significant wave height, (H_s) is defined as the mean height of the highest third of the waves. Given 3N zero up-crossing wave period, the significant height is,

$$H_S = \frac{1}{N}(H_{2N+1} + ... + H_{3N}) \tag{3-4}$$

where the heights H_1, ………., H_{3N} are arranged in increasing order (crest to trough heights were used in early research).

The period of a zero-up crossing wave is defined as the time interval between the two zero up crossings which bound it. Given a record of duration t minutes, the mean zero up crossing period is defined as,

$$T_Z = \frac{t \times 60}{\text{No. of zero up crossing waves on the record}} \text{sec} \tag{3-5}$$

A set of wind and wave data (Total 105128 observations) for the years January 1979 to December 2015 has been obtained based on observations at each grid point for the area of interest from BMT ARGOSS. Linear contour plot in Figure 3–5 is plotted using the recorded data from the observations of wave height H_s (m) against wave period, T_z (s) for each sea. The wave data of the Barents Sea is presented as a scatter diagram in Table 3-4. The wind speed measured at 10 m above sea level for the Barents Sea is also displayed as a scatter diagram in Table 3-5.

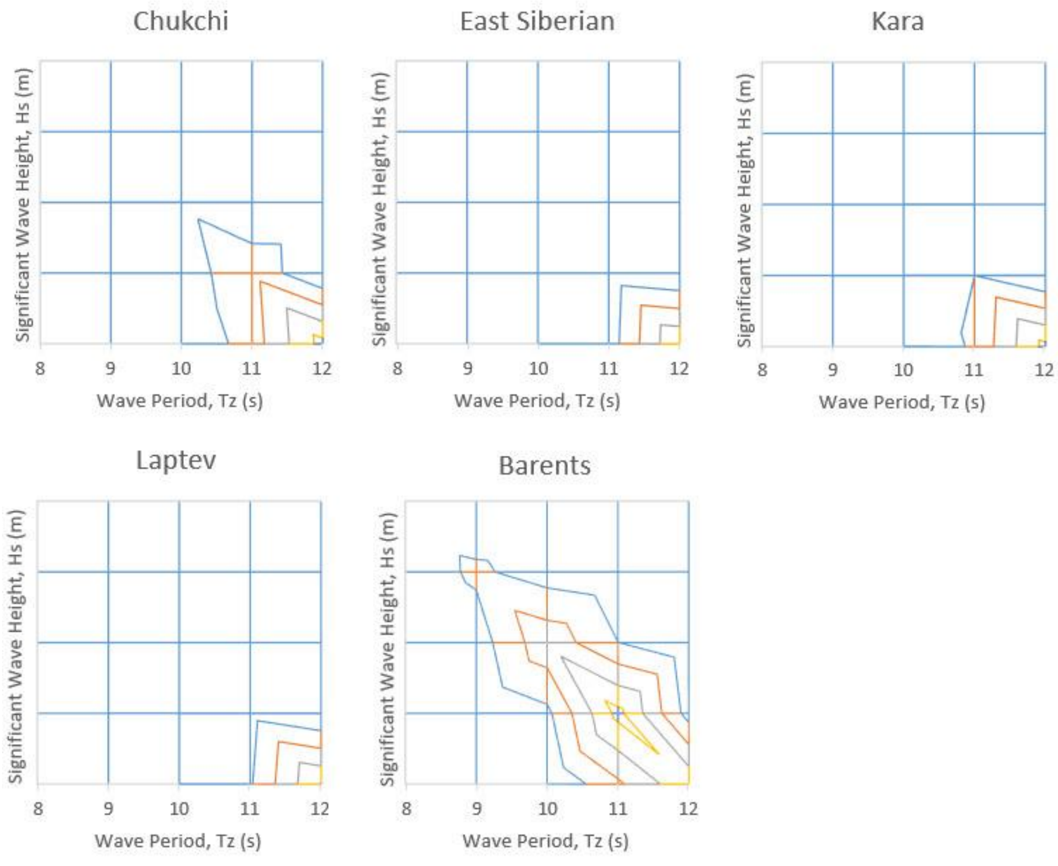

Figure 3–5: Linear contour plot of wave height data for each region on the NSR.

Table 3-4: Scatter diagram for observations of significant wave height and zero-up-crossing period of Barents Sea.

Sign. Wave Ht. (m)	Interval of zero-up-crossing period (s)									
	0 4.0	4.0 4.9	5.0 5.9	6.0 6.9	7.0 7.9	8.0 8.9	9.0 9.9	10.0 10.9	11.0 11.9	12.0 12.9
0 – 0.9	18946	2960	706	225	101	38	31	13	10	0
1.0 – 1.9	9084	21487	5048	857	170	58	24	4	6	2
2.0 – 2.9	3	3778	13441	2526	430	81	15	0	1	0
3.0 – 3.9	0	7	2444	5889	812	136	21	1	0	0
4.0 – 4.9	0	0	18	1916	2068	221	26	5	1	0
5.0 – 5.9	0	0	0	65	1207	423	55	4	4	0
6.0 – 6.9	0	0	0	0	98	505	56	2	0	0
7.0 – 7.9	0	0	0	0	5	109	87	4	0	0
8.0 – 8.9	0	0	0	0	0	6	68	3	0	0
9.0 – 9.9	0	0	0	0	0	0	14	4	2	0
10.0 – 10.9	0	0	0	0	0	0	0	3	0	0
11.0 – 11.9	0	0	0	0	0	0	0	2	2	0

Table 3-5: Scatter diagram for observations of significant wave height and wind speed of Barents Sea.

Wind Speed (m/s)	Interval of significant wave height (m)											
	0 0.9	1.0 1.9	2.0 2.9	3.0 3.9	4.0 4.9	5.0 5.9	6.0 6.9	7.0 7.9	8.0 8.9	9.0 9.9	10.0 10.9	11.0 11.9
0 – 0.2	50	19	3	1	0	0	0	0	0	0	0	0
0.3 – 1.5	1348	771	141	35	7	3	0	0	0	0	0	0
1.6 – 3.3	5074	2909	606	184	64	26	1	0	0	0	0	0
3.4 – 5.4	8729	7372	1852	457	126	49	8	1	0	0	0	0
5.5 – 7.9	6413	13895	4450	1189	367	81	21	2	2	1	0	0
8.0 – 10.7	1345	9508	7941	2660	757	214	44	9	1	2	0	0
10.8 – 13.8	70	2107	4483	3372	1598	503	122	35	5	0	0	0
13.9 – 17.1	1	158	761	1254	1086	646	295	72	15	3	2	0
17.2 – 20.7	0	1	38	153	232	215	143	70	46	4	0	3
20.8 – 24.4	0	0	0	5	18	21	26	16	7	10	1	1
24.5 – 28.4	0	0	0	0	0	0	1	0	1	0	0	0

The following equation is used to calculate the probability of significant wave height, $P(H_s)$ and wind speed, $P(u_{10})$:

$$P(H_s) = \frac{\textit{Number of wave height occurred in each level (e.g., 0\sim1)}}{\textit{Total Number of wave height that occurred}} \tag{3-6}$$

$$P(u_{10}) = \frac{\textit{Number of wind occurred in each level (e.g., 0\sim1)}}{\textit{Total Number of wind that occurred}} \tag{3-7}$$

The probability distribution of significant wave height, H_s and wind speed, u_{10} for five seas along the NSR are presented in Figure 3–6 and Figure 3–7, respectively. The probability distribution of significant wave height, H_s and wind speed, u_{10} for five seas along the NSR are presented in Table 3-6 and, Table 3-7 respectively.

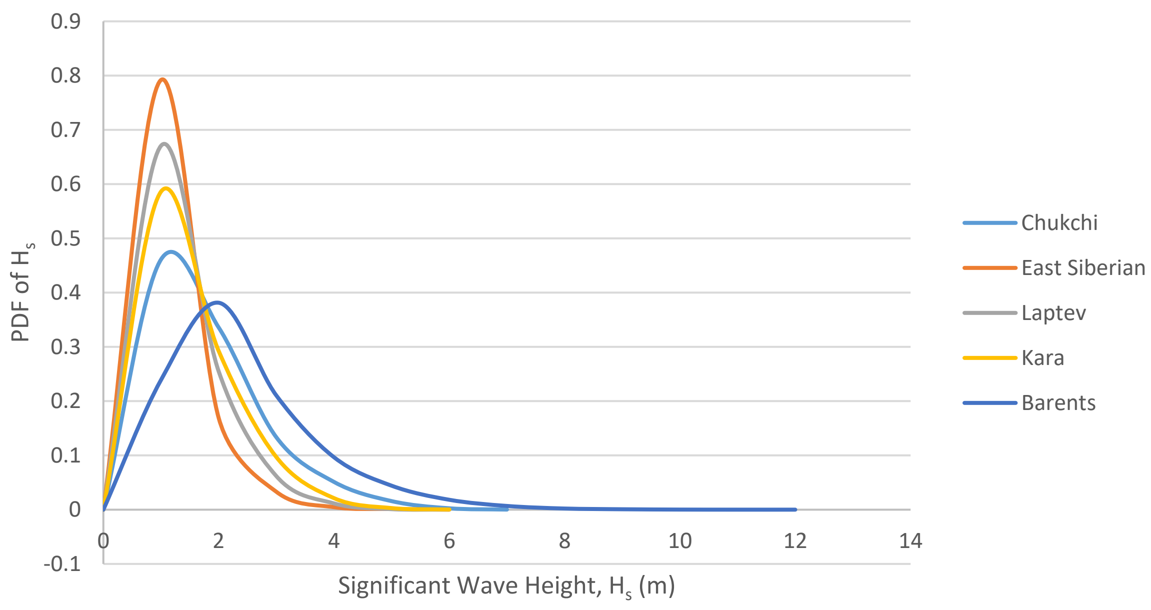

Figure 3–6: Probability distribution of significant wave height, H_s for five seas along the NSR.

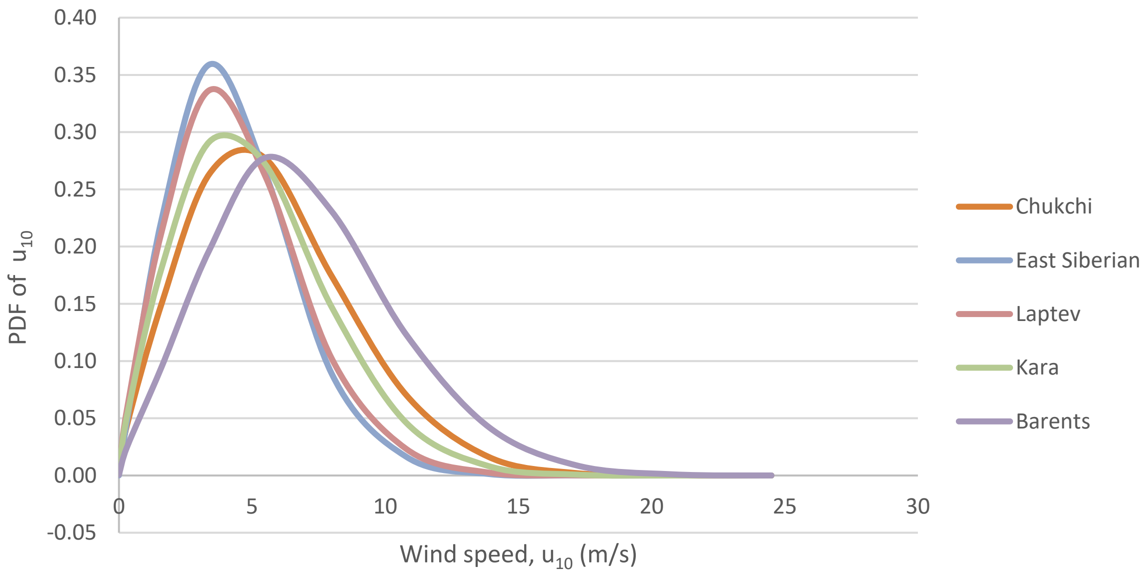

Figure 3–7: Probability distribution of wind speed, u_{10} for five seas along the NSR.

Table 3-6: Probability distribution of significant wind speed for five seas.

Beaufort No.	Scale Description	Wind speed (m/s)	Sea State	Chukchi	East Siberian	Laptev	Kara	Barents
0	Calm	0.0-0.2	S1	2.79E-03	NA	3.02E-03	1.66E-03	7.58E-04
1	Light Air	0.3-1.5	S2	3.35E-02	2.46E-02	4.03E-02	4.20E-02	2.39E-02
2	Light Breeze	1.6-3.3	S3	1.12E-01	1.48E-01	1.41E-01	1.43E-01	9.20E-02
3	Gentle Breeze	3.4-5.4	S4	2.24E-01	3.23E-01	2.77E-01	2.56E-01	1.93E-01
4	Moderate Breeze	5.5-7.9	S5	2.76E-01	3.24E-01	3.13E-01	2.88E-01	2.74E-01
5	Fresh Breeze	8.0-10.7	S6	2.12E-01	1.44E-01	1.70E-01	1.85E-01	2.33E-01
6	Strong Breeze	10.8-13.8	S7	1.07E-01	3.32E-02	4.95E-02	6.89E-02	1.28E-01
7	Near Gale	13.9-17.1	S8	2.90E-02	2.89E-03	5.90E-03	1.41E-02	4.46E-02
8	Gale	17.2-20.7	S9	3.88E-03	3.57E-04	4.64E-04	1.71E-03	9.39E-03
9	Severe Gale	20.8-24.4	S10	2.08E-04	NA	NA	2.72E-05	1.09E-03
10	Storm	24.5-28.4	S11	NA	NA	NA	NA	2.08E-05

Table 3-7: Probability distribution of significant wave height for five seas.

Sea State	Wave height (m)	Chukchi	East Siberian	Laptev	Kara	Barents
S1	0.0-0.9	4.61E-01	7.92E-01	6.71E-01	5.86E-01	2.39E-01
S2	1.0-1.9	3.36E-01	1.69E-01	2.55E-01	2.92E-01	3.81E-01
S3	2.0-2.9	1.33E-01	3.30E-02	6.19E-02	9.70E-02	2.10E-01
S4	3.0-3.9	5.12E-02	4.67E-03	1.15E-02	2.13E-02	9.66E-02
S5	4.0-4.9	1.58E-02	1.27E-03	9.94E-04	2.96E-03	4.42E-02
S6	5.0-5.9	2.56E-03	7.92E-05	6.63E-05	3.26E-04	1.82E-02
S7	6.0-6.9	1.67E-04	NA	NA	NA	6.86E-03
S8	7.0-7.9	NA	NA	NA	NA	2.13E-03
S9	8.0-8.9	NA	NA	NA	NA	7.99E-04
S10	9.0-9.9	NA	NA	NA	NA	2.08E-04
S11	10.0-10.9	NA	NA	NA	NA	3.11E-05
S12	11.0-11.9	NA	NA	NA	NA	4.15E-05

Through a carefully constructed BN, probability data can be incorporated to model the visibility issues, system navigation error, anchor failure, and assistance failure. The combined effect of different kinds of ice in Arctic water is recognised as one of the leading challenges for navigational purposes. The BN diagram for the integrated model of ship collision, foundering and grounding can be developed as illustrated in Figure 3–8.

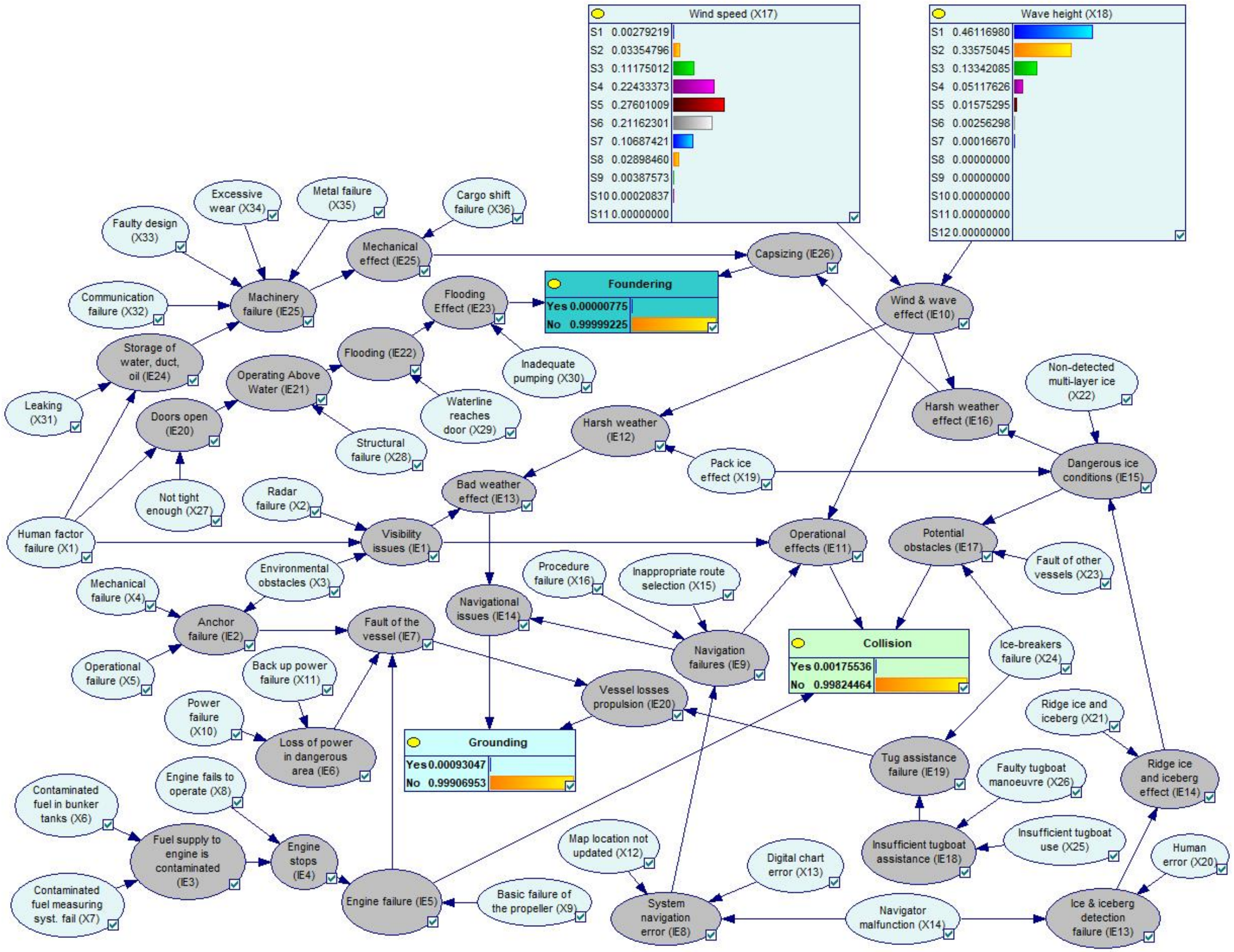

Figure 3–8: Graphical representation of the Bayesian network model.

3.4.3. Accident probability analysis

In this study, the potential safety measures to mitigate accidents, such as collision, foundering and grounding and their consequences on the NSR are not considered. The integrated model will help to predict the occurrence probability of any particular accident during ship navigation on the NSR. Different environmental and operational conditions based on case-specific scenarios are identified and considered as primary causes. By applying prior probabilities to these primary causes in the developed model, it is possible to identify most probable accidents that may occur in that region. The results presented in this section are obtained by using the BN model illustrated in Figure 3–8. The BN analysis demonstrates the highest collision, foundering and grounding probabilities to be in region 2 (East Siberian Sea) which are 3.31E-03, 1.34E-05 and 1.37E-03, respectively (Table 3-8).

Table 3-8: Accident probabilities of collision, foundering and grounding on the NSR.

Region	Sea	Collision	Foundering	Grounding
1	Chukchi Sea	1.76E-03	7.75E-06	9.30E-04
2	East Siberian Sea	3.31E-03	1.34E-05	1.37E-03
3	Laptev Sea	2.62E-03	8.96E-06	1.15E-03
4	Kara Sea	2.21E-03	2.43E-06	1.14E-03
5	Barents Sea	1.30E-03	3.11E-07	1.16E-03

Similarly, region 5 (Barents Sea) has the lowest probability regarding collision (1.30E-04) and foundering (3.11E-07) events. Region 1 (Chukchi Sea) represents the lowest probability (9.30E-04) regarding grounding event. However, due to extreme wind and wave effects, collision probability is almost similar in all five seas, and foundering probability is higher in region 1 (Chukchi Sea). Likewise, the likelihood of grounding event is higher in region 2 (East Siberian Sea). A comparison of collision probabilities in extreme and normal condition is presented in Table 3-9.

Table 3-9: Risk analysis of ship collision on the NSR in extreme and normal condition

Regions (Sea)	Conditions (Wind and wave effect)	Collision probability
Region 1 (Chukchi)	Extreme	5.03E-03
	Normal	1.76E-03
Region 2 (East Siberian)	Extreme	5.02E-03
	Normal	3.31E-03
Region 3 (Laptev)	Extreme	5.03E-03
	Normal	2.62E-03
Region 4 (Kara)	Extreme	5.01E-03
	Normal	2.21E-03
Region 5 (Barents)	Extreme	5.01E-03
	Normal	1.30E-03

3.4.4. Sensitivity analysis

A sensitivity analysis was performed to assess the sensitivity of the BN to some of the most critical variables. From Table 3-9, it can be seen that a significant change to collision probabilities on the NSR is noticed due to extreme weather condition (severe wind and wave effect). Therefore, any increase or decrease in probabilities of wind and wave effect are not considered in this sensitivity analysis. The main purpose of this study is to determine the factors that mainly contribute to the collision, foundering or grounding scenarios. Therefore, for each of the accidental events, a variation to each of the nodes that presented a higher contribution to the probability of the main event was changed systematically. From the analysis, it can be seen that a significant change in the probability of each node can make a difference to the probabilities of collision, foundering and grounding. A 10% increase in the initial probability of each node can make significant changes to the corresponding accident probability. For collision events, the changes take place for most of the nodes. Similar results occurred when each of the node probabilities is decreased by the same magnitude. For example, an increase of 10% in the probability of pack ice effect, non-detected multi-layer ice, and environmental obstacles made changes of 1.61%, 0.15%, and 0.13% in collision probability respectively. The results of the variation of the probabilities of the collision events when changing each of the initial node probabilities (Chukchi Sea) are presented in Figure 3–9.

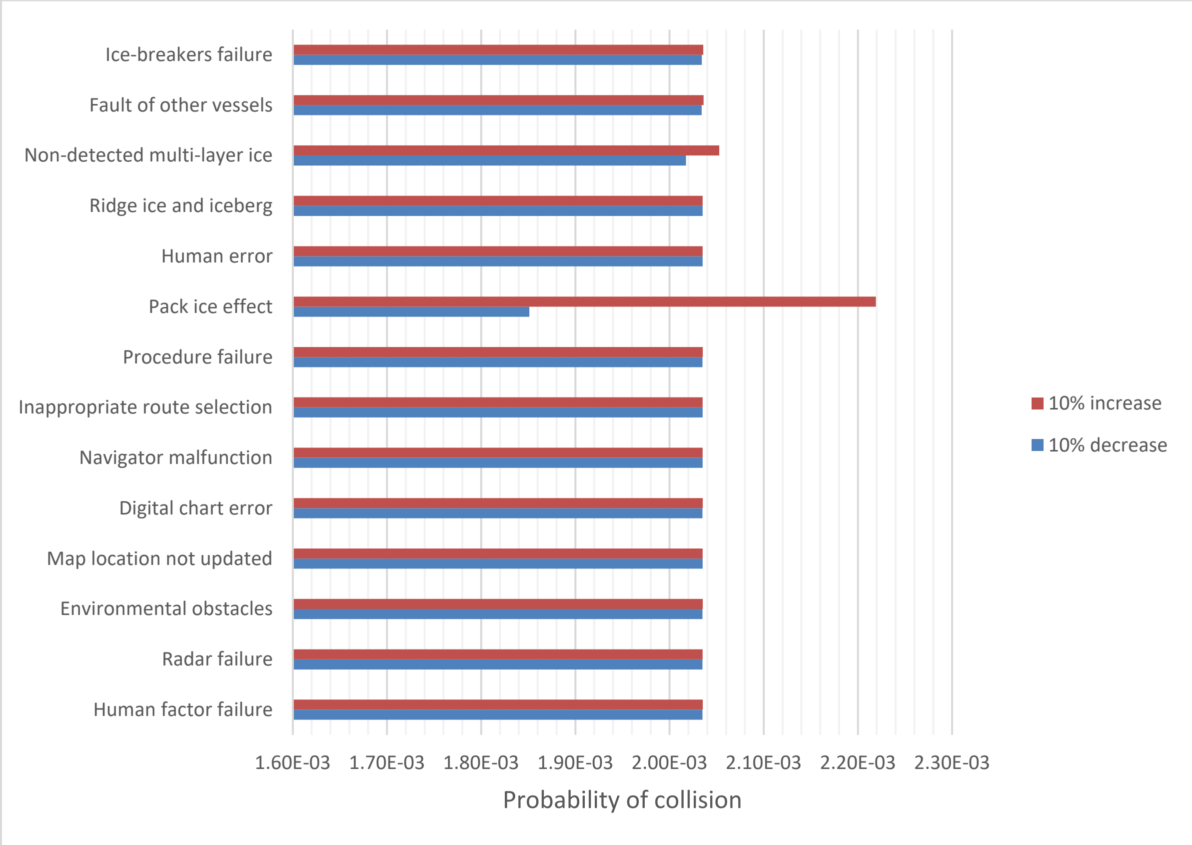

Figure 3–9: Sensitivity analysis of collision

Based on the sensitivity analysis, we have ranked the major causes of the collision events in the Chukchi Sea, which is shown in Table 3-10. From the table, it has been shown that “Pack ice effect”, “Non-detected multi-layer ice”, “Environmental obstacles”, “Digital chart error”, “Human factor failure”, “Radar failure” and ‘Procedure failure” impact significantly on ice-ship collision in the Chukchi Sea. The pack ice effect is more significant than the non-detected multi-layer ice in ice-ship collision event (1.61% > 0.15 %). Khan et al. (2017) performed a sensitivity analysis for the risk factors involved in the ice-oil tanker collision on the NSR and based on the analysis ranked environmental conditions at rank 3. Severe environmental conditions are the result of high ice and rough weather states. Wu et al. (2005) considered the logistics regression model to find determinants of the severity of fishing vessel incidents in the Canadian water. The sensitivity analysis from this model showed increasing severity due to wave height and ice concentration which can affect the stability and mobility of vessels adversely. The above sensitivity analysis allows investigating causes of an ice-ship collision in the Chukchi Sea by narrowing down major factors.

Table 3-10: Sensitivity analysis for the risk factors involved in ice-ship collision in the Chukchi Sea.

Ranking	Risk Factors
1	Pack ice effect
2	Non-detected multi-layer ice
3	Environmental obstacles
4	Digital chart error
5	Human factor failure
6	Radar failure
7	Procedure failure

For the cases of foundering event, the effect of pack ice is dominant compared to other accident causes with 0.011%. Besides, increase or decrease of the initial probability of each node represents very little change in foundering probability. In the case of grounding, if the probability of digital chart error is increased or decreased by 10%, there is a relative increase or decrease in grounding probability of 3.2% for instance. This is an increase from 9.30E-04 to 9.65E-04. Besides digital chart error (Couttie, 2013), other causes such as out of date map location, navigator malfunction, inappropriate route selection and procedure failure may play a more or less significant role in accident causation. The above analysis leads to the conclusion that some of the nodes are highly dominant in all three types of accidents.

3.5. Conclusion

The existing transportation accident models consider individual events and independent causation factors that may particularly lead to the accidents on the NSR. However, very often an accident is the outcome of non-sequential events caused by combined effects of different factors. Usually, accidents are time-dependent concerning evolving environmental and operational factors. This study focuses on developing a dynamic risk-based model to analyse shipping accidents in the Arctic waters to reduce the risk of accidents considering particular environmental and operational conditions. The developed method takes the advantages of case-specific data and updating mechanisms to reassess the risk. In the developed model, ship collisions with ice during navigation in Arctic routes were considered. Other accident scenarios, such as foundering, and grounding were also considered due to the likelihood of their taking place. Application of the developed methodology is reliant on BN modelling, due to the need for reassessing ship accident scenarios in Arctic transits in different conditions. The risk analysis revealed that the East Siberian Sea had the highest probabilities regarding collision, foundering and grounding of the ship. Other regions such as Chukchi, Laptev, Kara and the Barents Sea have almost similar probabilities regarding grounding. However, foundering probabilities are very low in all five areas. The sensitivity analysis of collision, foundering and grounding events also revealed that the developed model was sensitive to several environmental and operational conditions. From the BN and subsequent sensitivity analysis, it is clear that some of the root nodes are the dominant factors towards the accidental event. This contribution is the highest for collision and foundering where an increase of the initial probability leads to a significant change in the probability of the occurrence of accidental events. In the cases of grounding, this effect is less significant. The developed approach can be helpful for decision makers and safety experts to estimate the probability of different types of marine ship accidents considering the factors most contributing to the existing environmental and operational conditions. The developed methodology can be used to investigate the possibility of preventing and mitigating ship accidents in harsh and cold environments.

Acknowledgements

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Chapter 4: Dynamic risk model for marine vessel collision avoidance in narrow channel

The work presented in this chapter has been submitted for review in *Ocean Engineering*. The paper has been edited for inclusion into this thesis to improve readability. The citation for this research article is:

Baksh, A.-A, Abbassi, R., Garaniya, V. and Khan, F. (2018). Dynamic Risk Model for Marine Vessel Collision Avoidance in Narrow Channel. *Ocean Engineering* (submitted).

Abstract

Avoiding collisions in the port area or narrow channel is a crucial issue for the maritime industry. Marine collision avoidance risk model (MCAR) is a framework that uses sensors to locate nearby objects and estimate the level of risk, thus warning the operator of the vessel to take action to avoid or mitigate a potential collision. The main objective of this study is to develop a dynamic risk model for a vessel travelling through a narrow traffic way and hence to enable real-time decision-making to avoid stationary and non-stationary objects en-route. Five decision-making skills, viz. general skill, management training, technical knowledge, emergency response skill and sailing experience are considered as an integral part of the study. The proposed risk model is developed in Object-Oriented Bayesian Network (OOBN) framework considering different operational and environmental factors. The proposed dynamic risk model is applied through two case scenarios of the narrow channel. The estimated risk provides early warning to take appropriate preventive and mitigative measures to avoid a collision thus enhancing the overall safety of shipping operations.

4.1. Introduction

Collision avoidance is an essential task for any transportation system as well as in many other applications. Safety features such as a collision avoidance system (CAS) in a vehicle is relatively popular due to its detection capability of a nearby object thus alerting the driver to allow prevention of collision (NTSB, 2015). The CAS installed on a motor vehicle can sense any moving or non-moving objects in front of the vehicle considering object dimension and speed and reacts immediately to possible crash hazards by taking action such as alerting the driver and braking automatically. The modern car comprises several sensors, front, side and rear to alert the driver when it is close to nearby moving/non-moving objects thus avoiding a collision (Takatori and Hasegawa, 2006). These sensors are installed to alert the driver to proximity of an object allowing vehicle operators to adjust their position and minimise an accident. The potential benefits include a reduced number of fatalities and injuries, less severity of injuries and the savings of money by preventing potential damage to the vehicle and non-fatal injuries (Anderson et al., 2012; Jamson et al., 2008). Automotive insurers now even offer up to 20 percent discount on insurance premiums for vehicles equipped with such safety features (Anderson et al., 2012).

Modern vessels are equipped with radar, lidar and sensors to detect stationary and non-stationary objects en-route (Anderson et al., 2012; Jamson et al., 2008; NTSB, 2015; Takatori and Hasegawa, 2006; Tran et al., 2002). A moving vessel needs to maintain a safe distance from other marine objects, and marine vessels are equipped with the latest radar which is suitable for an open area allowing location of nearby objects. However, in a confined area or narrow channel, in the presence of stationary or non-stationary vessel/object, a vessel needs to react immediately to avoid potential collision taking into account vessel kinematics, different operational and environmental factors as well as human factors. This issue has been identified, and a possible solution proposed, that a ship can be equipped with sensors similar to an auto vehicle. These sensors can be installed on the hull to locate proximity of nearby objects in a narrow channel and to keep a safe distance, or maintain a significant distance, from other stationary or non-stationary objects. Therefore, a dynamic risk management system can be developed for marine vessel so that it could be useful when moving through a narrow channel. It can be beneficial in terms of collision avoidance for a marine vessel in the narrow and busy water channel, port and berth area and narrow river channel. It can be effective by warning the operator of a vessel of a potential collision threat whilst travelling along a narrow trafficway. The proposed dynamic risk-based model is implemented through a case scenario of a narrow river channel to see the potential benefits of the model. In the proposed model, if a real-time observation is provided such as vessel kinematics (approximate distance between the vessels, own vessel speed, and manoeuvring condition, target vessel type, length and speed), different operational and environmental state (navigation state, environment and weather state) as well as human factor state, then it may be possible to predict the level of risk and take effective action in real-time. Once the new information is added to the system of the moving vessel, the system will continue to update any risk of collision.

4.1.1. Literature review on existing collision avoidance technology

Several methods have been applied to estimate the accident causation probability in maritime risk and consequence assessment. Among ship accidents, ship-ship collision has been the focus of many related studies in recent years (Goerlandt et al., 2015; Goerlandt et al., 2012a; Montewka et al., 2011a; Montewka et al., 2012; Montewka et al., 2011b; Montewka et al., 2010; Qu et al., 2011). Fujii et al. (1970) and Macduff

(1974) used the concept of collision diameter which is defined as the contact of two vessels at a distance (Pedersen, 1995). Gluver and Olsen (1998) utilised ship domain approach to assess ship to fixed object collision. Fowler and Sørgård (2000) used the critical situation criteria which is defined as a close encounter of two vessels within a certain distance. Tran et al. (2002) developed a unified collision avoidance system for a marine operation called MANTIS. Kaneko (2002) proposed a collision model to encounter probability estimation which is defined as a critical area in rectangular and circular shape around a vessel where a violation of that area means a collision. Pedersen (2002) published a series of papers based on collision assessment of a ship with a fixed object. Montewka et al. (2010) proposed the MDTC (Minimum Distance To Collision) geometrical model for the ship to ship collision probability estimation. Mou et al. (2010) established a risk assessment model and used the Automatic Identification System (AIS) data to study collision avoidance in busy waterways by taking into consideration ship collision data. Qu et al. (2011) studied ship collision risks in the Singapore Strait by considering real-time ship location and vessel speed. Montewka et al. (2011a) defined a critical situation as the close encounter of two vessels within a distance of 0.5 Nm and considered this value as constant regardless of any contact between those two vessels. The Airborne Collision Avoidance System (ACAS) has been already introduced in (Baldauf et al., 2014; Baldauf et al., 2015) for the maritime domain. Further this method was extended as Maritime Traffic Alert and Collision Avoidance System (MTCAS) in (Baldauf et al., 2017; Denker et al., 2016). According to Baldauf et al. (2017), to trigger a perfect collision alarm a comprehensive network of sensors to provide accurate and reliable data of own vessel, marine environment and targets in the vicinity was greatly needed. Szlapczynski and Szlapczynska (2017) presented a Collision Threat Parameters Area (CTPA) display based technique featuring a manoeuvre simulation mode to assist the navigator in advance to see the results of a planned manoeuvre (combinations of own course and speed with respect to time as well as target-colliding and landmass-colliding). Szlapczynski and Krata (2018) further extended the method by utilising detailed modelling of own ship dynamics viz. course alteration manoeuvres and supports navigation for harsh weather conditions. For other collision models, see Merrick et al. (2003), Goerlandt and Kujala (2011), Montewka et al. (2011b), Goerlandt et al. (2012a) and Goerlandt et al. (2015).

4.1.2. Discussion of existing accident models

Most of the studies discussed above focused on a collision model for open waters. Several authors have considered ship safety domain and collision diameter as a safe distance to avoid contact with other vessels. AIS data has been used to study the collision avoidance. Automatic Radar Plotting AIDS (ARPA), a computer assisted radar data processing system is introduced to provide ship course, speed, range, and closest point of approach (NIMA, 2001). Integration of both ARPA and AIS with Electronic Charts (EC) (Weintrit, 2009) has resulted the concept of e-navigation. However, use of a sensor on a ship hull similar to RADAR system, such as that used in the automotive industry to locate a stationary and non-stationary object in near proximity and act in real-time, is comparatively an updated approach in the marine industry. The proposed decision-making skills in each step of estimated risk have never before been considered in a collision avoidance system. Conventional models developed for collision avoidance system uses fault tree, event tree and Bayesian Network (BN). However, use of Object-Oriented Bayesian Network (OOBN) in marine collision avoidance system is a relatively new concept. In this study, OOBNs are favoured over conventional methods due to advantages such as distinct subclass for a complex network, encapsulated subnetwork for individual analysis of root causes, and addition/subtraction of new nodes without modifying the entire network. Additionally, features of BN include conditional dependency between root causes and consequences, common cause issues between the connected nodes, the addition of new accident prior probability as well as updating the real-time posterior probability in the model. The advantage of the proposed method is its capability to predict the level of risk considering ship kinematics, environmental and operational factors, as well as human factors. The estimated risk provides early warning to take appropriate mitigative measures in conjunction with decision-making skills to avoid collision in advance which enhances overall reliability of the shipping operations.

The present study aims to develop a novel methodology by using the OOBN to represent potential collision scenarios in the narrow channel or port areas considering vessel kinematics, different operational and environmental factors as well as human factors to quantify the level of risk. Using OOBNs, the probabilities of different level of risk in narrow channels are quantified based on primary causes and their associated probabilities. The proposed methodology relies on historical data and past literature reviews in the estimation of the probability distributions of primary events. The primary objective is to mitigate the collision risk to be as low as reasonably practicable (ALARP). Different collision scenarios that are likely to occur during transit in narrow channels are studied. Two different case studies, which exemplify the application of the developed methodology, are also presented.

This paper is structured in four main sections: Section 4.2 discusses the OOBN briefly and Section 4.3 explains the concept, methodology and collision scenarios. This is followed by two case studies on risk estimation and a brief discussion in Section 4.4. The analysis of the results is discussed in Section 4.4 while concluding remarks are discussed in Section 4.5.

4.2. Object-Oriented Bayesian Network (OOBN)

The BN is referred to as a directed acyclic graph (DAG), consisting of nodes and links connecting the nodes (Jensen and Nielsen, 2007; Pearl, 1988). The nodes represent discrete and/or continuous random variables, and directed arcs imply local conditional dependencies between parent and child nodes (Ghahramani, 1998; Jensen and Nielsen, 2007; Neapolitan, 2003; Pearl, 1988). Each node is associated with its probability distribution which is marginal for nodes having no incoming arcs and is conditional for the other nodes. Although BNs have widely been used successfully in many disciplines, they are inadequate when modelling large complex domains (Koller and Pfeffer, 1997). The OOBNs can overcome such complex model domains and the use of OOBN enables the construction of complex and dynamic models (Koller and Pfeffer, 1997).

The OOBNs are an extension of classical BNs which possess all advantages of classic Bayesian networks and contain instance nodes in addition to the classical nodes. An instance node represents an instance of another network, which could in itself contain instance nodes. An instance node is an abstraction of a network fragment into a single unit (Jensen and Nielsen, 2007; Koller and Pfeffer, 1997). The main advantage of the object-oriented approach is the ability to define object classes that inherit the properties of other classes. A class is a generic network encapsulation; however when this class is instantiated it is called an object. A class may be instantiated many times in a model (Jensen and Nielsen, 2007) and may share common subclasses. These subclasses can inherit common properties from the parent class which can be modified and enhanced. An advantageous characteristic of object-oriented modelling is to create subclasses that inherit properties from another class (Koller and Pfeffer, 1997).

A complex object comprises a set of attributes, and each attribute represents an object. Each of these objects is composed of input, encapsulated, and output nodes. An input node contains basic variables; however, encapsulated and output nodes are referred to as simple objects. A sample OOBN is presented in Figure 4–1.

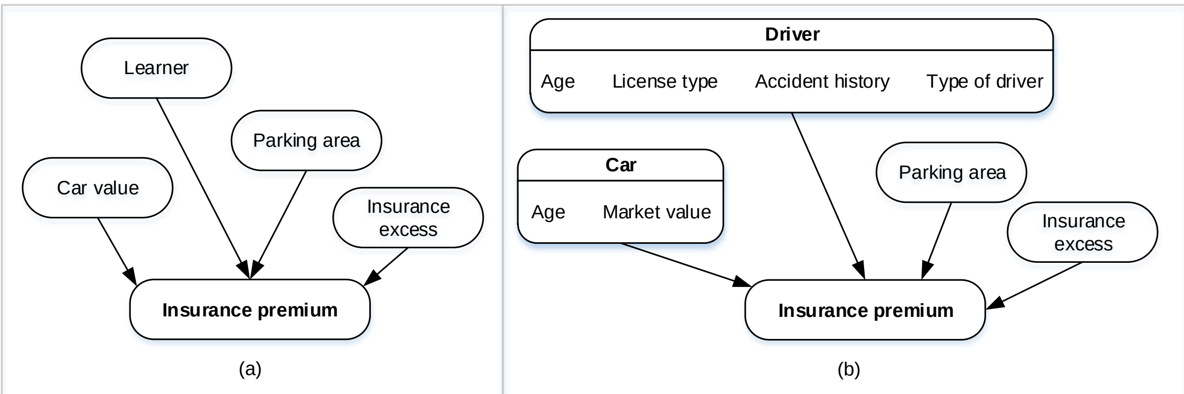

Figure 4–1: (a) A typical BN of car insurance premium for a learner. (b) OOBN model of car insurance premium for all type of drivers.

4.3. Proposed methodology for vessel collision alert in the confined area

In the following sections, a natural framework for maritime risk analysis in a narrow channel is discussed in detail. A flowchart of the proposed model is shown in Figure 4–2 to ensure a step-by-step systematic process.

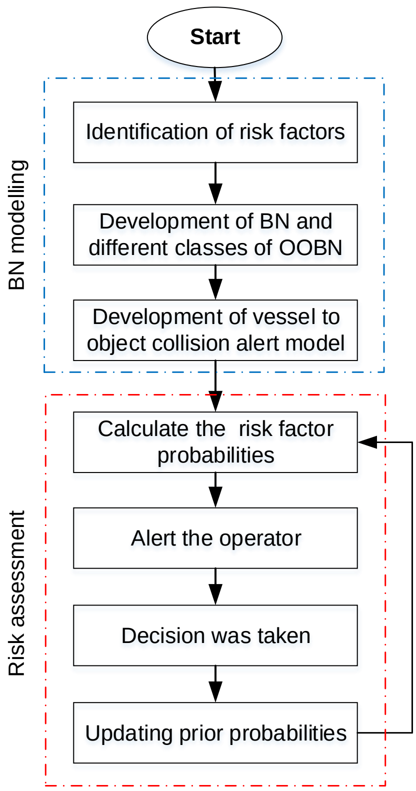

Figure 4–2: Developed risk-based methodology for risk analysis in a confined area for an accident scenario.

4.3.1. Risk factors in the confined area

Maintaining at least a minimum safe distance from the nearest object considering environmental and operational conditions is the biggest challenge for marine vessels. Risk factors such as navigational state (e.g., effectiveness of rudder, bow thruster, mechanical device, sensors, location detection, weather update, and communication), and environmental obstacles (e.g., current, fog, wind, wave, luminous background and seasonal effect) may play a crucial role in the ship to stationary/non-stationary object collision. Vessel safety is very important in terms of maintaining speed in a confined area in addition to effectiveness of manoeuvring devices (bow thruster, rudder and machinery), location detection devices (echo sounder, GPS, RADAR, AIS, ARPA and ECDIS), communication devices (VHF radio and satellite antennae), weather update devices (NAVTEX, VHF radio, satellite broadcast, current indicator and weather facsimile) and hull sensor. Shipping companies follow a standard safety checklist to ensure all statutory regulations comply with destination port requirements before arrival. It is necessary to check all mechanical issues before entering the port area. In terms of any mechanical failure, it could cause disruption en-route and to the flow of traffic in the port area.

Large vessels such as cargo carriers, passenger carriers, fishing vessels and oil tankers are of different sizes and weights. These types of vessels can maintain a stable speed in an open sea; however, it is challenging to maintain the same steadiness in a narrow channel or port area. When a vessel enters the port area with a stable speed, its course becomes difficult in the presence of cross-winds and cross-currents as both interfere with the maneuverability of the vessel. Furthermore, the presence of large vessels in a narrow channel may cause vessel induced waves which may result in a change to the water flow and thus to the currents. However, in the presence of two large vessels in a narrow channel, pressure is developed from both sides of both vessels which tends to divert both vessels from their pathway (Kray, 1973). According to PIANC (1980), at least twice the beam of the larger ship is required as a safe distance between large vessels in a two-way channel. Vessel length is important to measure safe distances on port and starboard sides of a vessel on any route. A comparison of typical cargo and passenger vessel dimensions adopted from Tsinker (1997) are illustrated in Table 4-1.

Table 4-1: Typical cargo and passenger vessel dimensions

Tonnage	Length (m)	Width (m)	Depth (m)	Fully Loaded Draft (m)	Displacement (t)
Cargo Boats					
700	52	8.3	3.8	3.6	900
4000	100	14.3	7.7	6.3	5300
7000	124	17.0	9.6	7.5	9300
10000	142	19.0	11.1	8.3	13300
20000	184	23.6	14.6	10.3	26700
Passenger Boats					
500	50	8.2	4.5	4.0	500
4000	105	14.8	8.0	6.3	4000
8000	135	18.2	10.8	8.0	8000
20000	180	23.0	13.8	9.0	20000
80000	290	36.0	21.0	11.7	80000
Ore Carriers					
1000	61	8.9	4.8	3.3	1300
4000	96	13.9	7.5	6.1	5300
20000	164	23.4	12.7	9.2	26700
50000	222	31.4	17.1	11.7	66700
100000	278	39.3	21.4	14.0	133300
Tankers					
300	37	7.0	3.3	3.0	400
4000	96	14.0	7.2	6.2	5300
20000	164	23.7	12.3	9.5	26700
50000	222	32.0	16.7	12.2	66700
120000	297	42.6	22.4	15.5	160000

Environmental factors such as fog, heavy wind, high wave, luminous background and current may affect the operation of the moving vessel. Fog reduces visibility and can effectively hamper vessel movements. Luminous background at sea or in the port area may affect usual visibility. There are two types of fog; summer and winter. The wind is considered to be the primary cause of waves. Wind movement may affect marine vessel operations while entering and departing the port area, and during manoeuvering in port and confined areas. The wind effect can cause the marine vessel to oscillate, and sufficient wind can drift the vessel sideways or at an angle. A cross-wind has the greatest effects on a vessel while sailing at low speed, particularly large vessels sailing with large areas exposed to the wind. Wind effects on marine operations including marine vessels and port facilities are adopted from Myers et al. (1969) and illustrated in Figure 4–2.

Table 4-2: Wind effects on marine operations.

Beaufort scale		Wind speed (knots)	Effect on marine operations: Marine Vessels	Effect on marine operations: Port Facilities
0	Calm	0-1		
1	Light air	1-3		
2	Light breeze	4-6		
3	Gentle breeze	7-10		
4	Moderate breeze	11-16		
5	Fresh breeze	17-21	↑	
6	Strong breeze	22-27	Berthing limit	↑
			↓	Crane operations cease ↓
7	Near gale	28-33	Tugboat limit	↑
8	Fresh gale	34-40	Ferry operations cease	Loading arms disconnected
9	Strong gale	41-47	Emergency mooring lines	↓
10	Whole gale	48-55	Larger vessels put to sea	Facilities secured, cranes lashed, etc.
11	Storm	56-63		
12	Hurricane	64-71		

Ship motion is greatly influenced when the frequency of the wave encounter with the natural frequency of the ship (Tsinker, 1997). According to (PIANC, 1980, 1985), only long-period waves (greater than 9 s or periods in excess of 16 min) need to be addressed for large ships if considering an increase in draft of ships due to wave response. Shorter waves significantly have no effects on natural frequency of large ships. On the contrary, open ocean long-period waves known as seiches may cause substantial damage to both ship and mooring structures. When a ship enters enclosed harbours, long period waves may be further amplified, and natural water oscillation may develop. Two different types of waves such as short period (3 to 30s) and long period or seiche (period in excess of 16 mins) are considered during vessel navigation (Tsinker, 1997). Additionally, large waves known as vessel induced waves can be generated due to the movement of large vessels and can be classified as bow waves, transverse stern waves, and secondary waves. These waves follow the same mechanism as for wind waves and are highly dependent on vessel speed, hull shape, water depth, and the block-age ratio of the vessel to channel cross section (Tsinker, 1997; Tsinker, 2004). In a confined waterway, the magnitude of the transverse stern wave is comparatively higher than the bow wave. Drift forces caused by the wave may have a significant influence on vessel maneuverability though it may not have enough impact when sailing on a straight course (Delft-Hydraulics-Laboratory, 1984). Different types of vessels such as cabin cruiser, tugboat, barge and tanker and their approximate generated wave heights, have been adopted from Sorenson (1973) and are illustrated in Table 4-3.

Table 4-3: Different vessel generated wave heights.

							Distance from Sailing Line (m)		
Vessel type	Length (m)	Beam (m)	Draft (m)	Displacement (kg)	Water depth (m)	Speed (m/s)	30.5 H_{max} (m)	152.4 H_{max} (m)	304.8 H_{max} (m)
Cabin cruiser	7.0	2.5	0.5	2722	12.2	3.1	0.2	0.1	
						5.1	0.4	0.2	
Tugboat	13.7	4.0	1.8	26309	11.3	3.1	0.2	0.1	
						5.1	0.5	0.3	
Barge	80.2	16.8	4.3	4917000	12.8	5.1	0.4	0.2	0.1
Moore dry dock tanker	153.6	20.1	8.5	17.1E06	17.1	7.2		0.5	0.3
						9.3		1.6	1.4

Currents influence vessel movement and may change the wave characteristics while on course. An opposing current may decrease the wavelength and increase the height of the wave. The tidal currents generally change four times a day which can have a profound effect on vessels approaching the port and while moored at the berth. Additionally, cross-currents may affect the vessel navigation. In some ports, vessel navigation is restricted during the tidal cycle or current windows due to strong current. Lack of knowledge on adverse environmental conditions and timely weather forecasts may result in uncertainties in ship manoeuvrability while navigating through the channel.

Human error effect on detection failure is recognised as one of the recurrent causal factors for vessel collision. Human error and visibility are identified as significant contributors to marine ship collisions (Fowler and Sørgård, 2000; Macrae, 2009; Van Dorp et al., 2001). Rothblum et al. (2002) stated that about 80% or more of such accidents involve human-related error factors. Some of the most common human-related errors such as interpretation failure, fatigue/sleeplessness, alcohol abuse, lack of technical knowledge of ship systems, and poor communication are examples (2002; Dhillon, 2007; Talley, 2002; Uğurlu et al., 2015). According to an investigation into a typical number of collision cases, a major lack of situational awareness is identified as a major cause (Liu and Wu, 2004). NTSB (1981) recommends improving internal communication between shipmates and crew members, masters to pilots, and other communication such as ship to ship, and ship to VTS on board. Experienced shipmasters or ship pilots can react promptly to a stressful situation. One of the main tasks of bridge officers is to maintain safe navigation during voyage planning. Misunderstandings between shipmasters and the bridge personnel can lead to a possible collision or grounding. If crews are unable to maintain a safety level in the sequence of events leading to a collision, it is often concluded as a case of incomplete or incorrect execution of tasks (Baldauf et al., 2017). While manoeuvering large ships in confined areas (e.g. port, narrow channel) or in busy traffic, knowledge of particular areas is essential along with experience for accurate and safe maneuvering.

Potential risk factors for ship to stationary/non-stationary object collision in a port area are illustrated in Table 4-4.

Table 4-4: Risk factors associated with ship to stationary/non-stationary object collision.

OOBN classes	Risk factors
Human factor state	Interpretation failure Fatigue Poor watchkeeping Individual failures Lack of communication between vessels Lack of communication between master and pilot Lack of communication in bridge team management Onboard communication failures Lack of emergency awareness Inexperienced sailor
Navigational and manoeuvring equipment state	Rudder failure Machinery failure Bow thruster failure Manoeuvring device failure Inactivated ECDIS Sensor failure Echo sounder failure GPS failure Navigational equipment failure Tug failure
Low visibility	Fog effect Bad weather Luminous background
Environment state	High wind High wave Vessel induced wave Strong current
	Own vessel speed Target vessel distance Target vessel speed Target vessel length (m) Target vessel type

4.3.2. OOBN construction for risk factors

The following classes comprise the OOBN model: (a) human factor state, (b) navigational and manoeuvring equipment state, (c) low visibility, and (d) environment state. Other risk factors such as own vessel speed and manoeuvring condition, target vessel distance, target vessel type, length and speed are also added as important factors in the OOBN model. Different vessels such as cargo carriers, oil tankers, LNG/LPG carriers, passenger carriers and fishing vessels differ in length, speed and carrying capacity. Ship to stationary/non-stationary object collision consequences are reflected through the integration of the above classes in the OOBN. The output from each class is connected to other nodes or consequences. Table 4-4 explains the dependency among the OOBN nodes in the proposed model.

4.3.3. Human factor state

Collision avoidance is one of the most important tasks for the watchkeeper on a ship's bridge (Baldauf et al., 2017). The shipmaster is responsible for critical decision making in case of emergency for the safety of vessels, crews and the environment. A crew should possess adequate technical knowledge of their own ship and be aware of safety measures in a crisis. Shipmasters and officers should be fully aware of the limitations of the vessel and maintain a safe distance from any object while en-route. In terms of unacceptable risk, shipmasters need to take action. Considering the factors "Individual failures", "Onboard communication failures", "Inexperienced sailor" and "Lack of emergency awareness", Figure 4–3 shows a small BN of the "Human factor failure" model. The internal node "Human factor failure" is dependent on the inputs of Individual failures, Onboard communication failures, Inexperienced sailor and Lack of emergency awareness. The output node, "Human factor failure", is a Boolean node with possible values of "Yes" and "No".

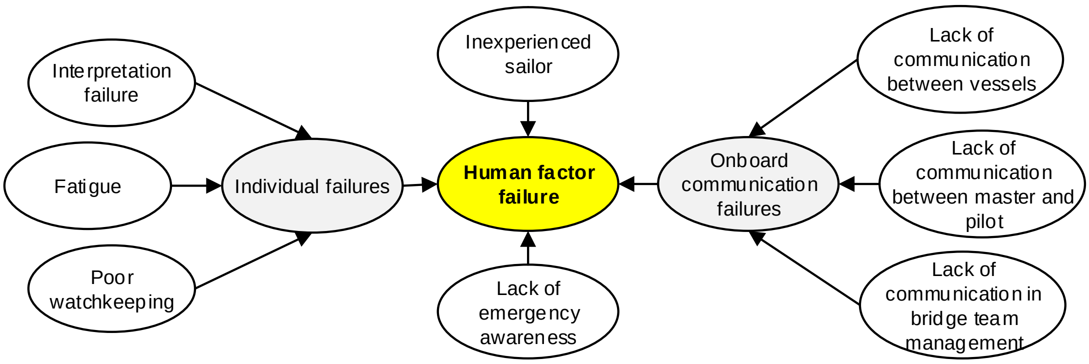

Figure 4–3: OOBN for Human factor failure.

4.3.4. Navigational and manoeuvring equipment state

The effectiveness of bow thruster and rudder are important for safe maneuverability in the port area. In addition to the above devices, tug assistance also contributes to safe navigation. Any mechanical or navigational issues could interrupt steadiness of the vessel in a confined area or open sea. In Figure 4–4, the OOBN model uses the internal node "Manoeuvring device failure" as a dependent node on the three input nodes: Rudder failure, Machinery failure, and Bow thruster failure. The internal node, "Navigational equipment failure", also depends on the four input nodes of Inactivated ECDIS, Sensor failure, Echo-sounder failure and GPS failure. Therefore, "Navigational and manoeuvring equipment failures" is also dependent on another set of inputs defined by the nodes "Manoeuvring device failure", "Navigational equipment failure", and "Tug failure" (Figure 4–4). These internal nodes also influence the output node "Navigational and manoeuvring equipment failures". The output node, "Navigational and manoeuvring equipment failures", is a Boolean node that shows "Fail" and "Work" as the two outcomes.

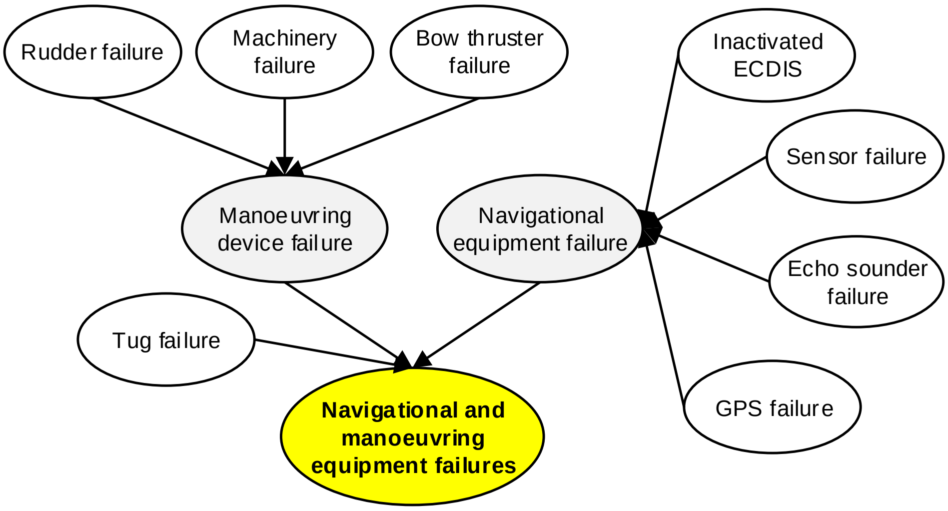

Figure 4–4: OOBN for Navigational and manoeuvring equipment failures.

4.3.5. Low visibility

The node "Low visibility" is dependent on fog effect, bad weather and luminous background. Two different types of fog, such as Summer and Winter, influence the Fog effect and are highly dependent on Season. In Figure 4–5, OOBN model of the low visibility state is illustrated.

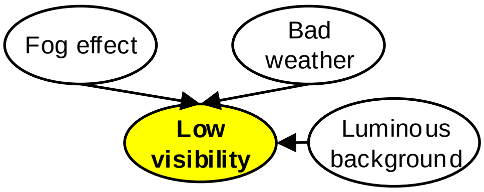

Figure 4–5: OOBN for Low visibility state.

4.3.6. Environment state

Environmental factors such as high wind, high wave and strong current may affect navigation. In Figure 4–6, OOBN model of the environment state is illustrated. High wave (including swell) is dependent on high wind and vessel induced wave. The wind effect is considered as the primary cause of waves. The strong current can deviate the vessel from actual speed. The output node "Environment state" becomes dependent on the node “High wave” and “Strong current” in the model. The output node “Environment state” shows Boolean values “Yes” and “No” as the outcome.

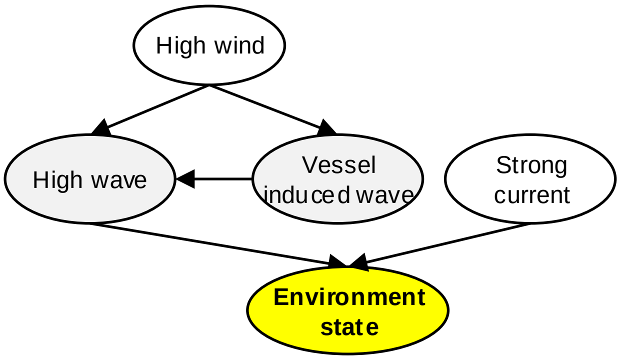

Figure 4–6: OOBN for Environment state.

4.3.7. Decision-making skills

Decision making is appropriate whenever ships need to manoeuvre and pass at a safe distance in typical situations. To take necessary steps upon a warning, in every step each individual need some required skills. In an emergency, these skills might differ based on different conditions such as open water, busy traffic, extreme weather and external attack (piracy or terrorist attack). In this study the following decision-making skills are proposed (Figure 4–7):

1. General skill requirement (GSR): General skills gained during initial training on shore and/or on board the ship through the training requirement outlined in the IMO’s international convention on Standards of Training, Certification and Watchkeeping (STCW) for Seafarers, in its 1995 revised version as amended for basic navigational technique skills.

2. Management training requirement (MTR): Management training obtained through higher training and onboard work experience to be skilled in bridge resource management and bridge teamwork.

3. Technical knowledge requirement (TKR): Technical knowledge gained through academic knowledge outlined in STCW 95 as amended and exposure to onboard navigational equipment to make the best use of those navigational aids in any situation.

4. Emergency skill requirement: Emergency response responsibilities and situational awareness has to be gained by every mariner through the pre-sea course, academic course and onboard drill and training as per SOLAS, MARPOL and STCW.

5. Sailing experience requirement (SER): Sailing experience is gained through mandatory sailing requirement outlined in STCW 95 as amended for keeping continuity or career progress by securing higher ranks as well as shipping industry requirements for employment and promotion.

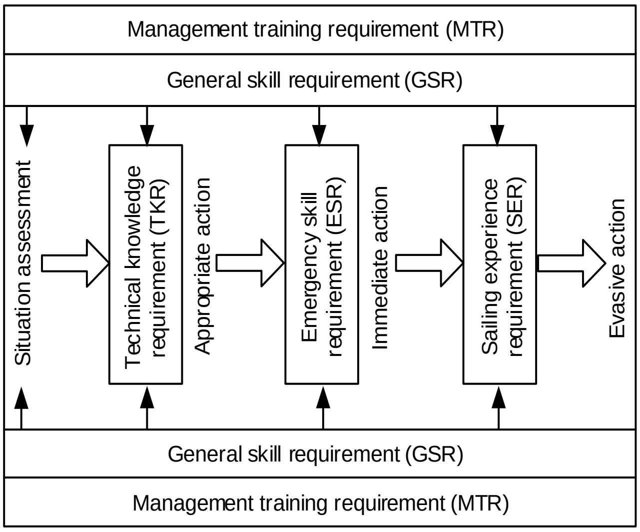

Figure 4–7: MCAR decision-making skills.

General skill and management training are essential in every step to cope with the situation (e.g., from situation assessment to evasive action). Any wrong decision by the shipmaster can be a failure to take appropriate action to avoid a collision. The decision-making process should be supported by appropriate warning in time. As illustrated in Fig. 7 the decision-making process consists of four elements: "Situation assessment", "Appropriate action", "Immediate action" and "Evasive action". In an emergency when the first warning is activated, it is necessary to assess the situation (internal and external) for further decisions. At this step, general skills and management training of the crew and shipmaster are necessary. If for any reason the situation assessment is not properly evaluated then a second warning will be activated which requires technical knowledge along with general skills and training to allow appropriate action. Immediate action is needed once the third warning is enabled which involves emergency response skills along with general skills and training. If there is a failure to act on previous warnings, the last and final warning will be activated for evasive action which requires sailing experience along with general skills and training. The prior probabilities of these decision-making skills are calculated using evidence from previous literature (Baksh et al., 2015; Rathnayaka et al., 2011; Rathnayaka et al., 2013), past experience and expert judgment (Table 4-5).

Table 4-5: Prior failure probability of each decision-making skill.

Safety barrier(x_i)	Failure probability P(x_i)
General skill requirement (GSR)	2.90×10^{-3}
Management training requirement (MTR)	4.21×10^{-2}
Technical knowledge requirement (TKR)	5.27×10^{-2}
Emergency skill requirement (ESR)	2.71×10^{-2}
Sailing experience requirement (SER)	10.88×10^{-2}

4.3.8. Collision alert and decision-making

In a narrow channel or confined area, vessel movements can occur in the same direction, opposite direction or at an angle (viz. 90º between vessels). The safe distance between two queuing ships in a port area depends on the ships' sizes, that is; (i) 1 nautical mile (nm) in between (over 20,000 g.r.t), (ii) 0.5 nm in between (500 g.r.t ~

20,000 g.r.t), and (iii) 4 times a ship's length for ships under 500 g.r.t (Hsu, 2014). According to IMO (Nautical-Institute, 2013), the safe distance (Figure 4–8) to comply with collision regulations is as follows:

- Port side of any route: 6 ship lengths + 500 m
- Starboard side of any route: 0.3 nautical mile (nm) + 6 ship lengths + 500 m

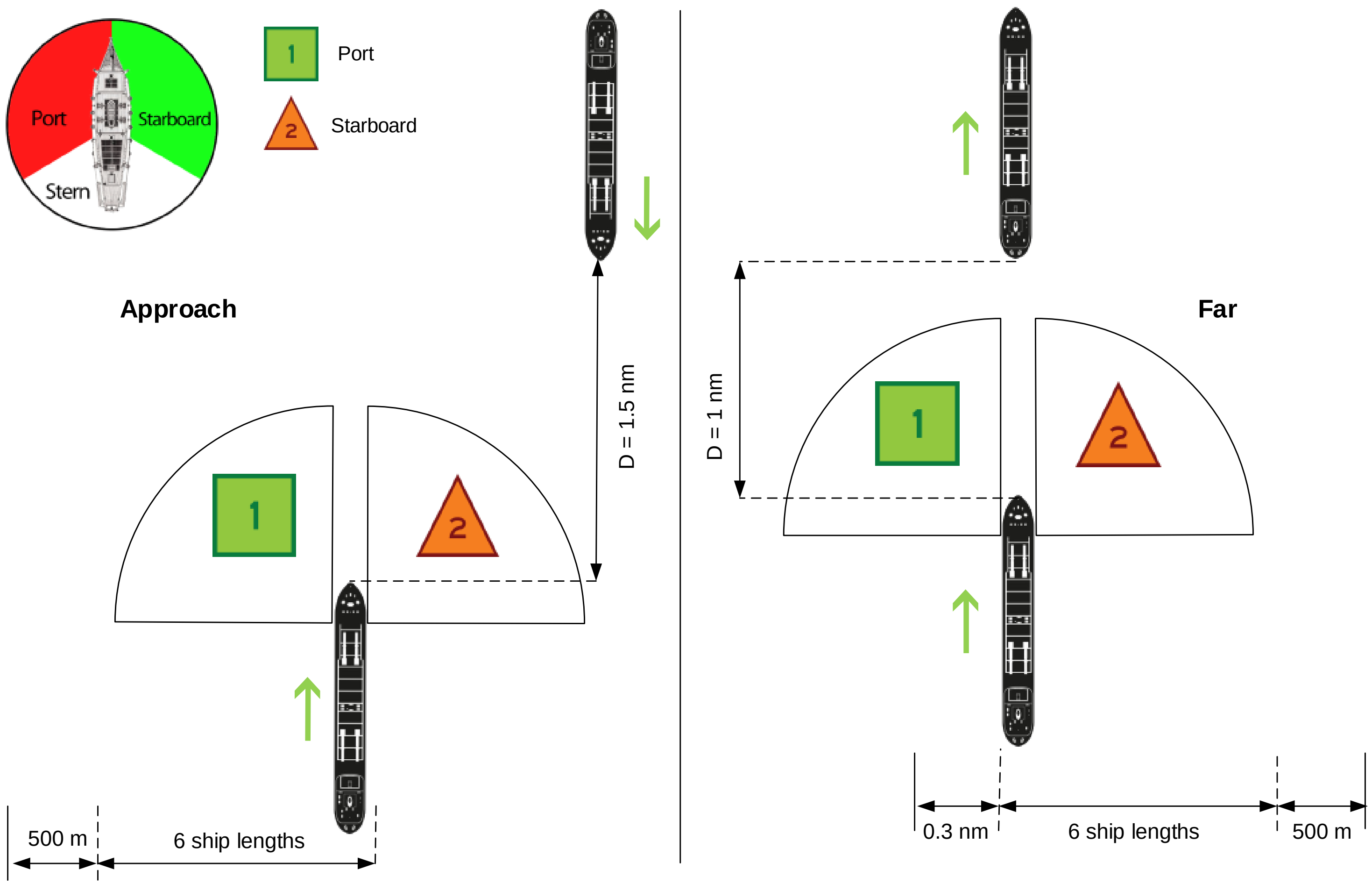

Figure 4–8: Safe distance on port and starboard side of a vessel on any route according to IMO (Nautical-Institute, 2013).

For example, two vessels are heading in the same direction (Figure 4–9) in the port area, and the distance between them is about 3000 m. If the host vessel is 160 m in length, then the required safe distance to manoeuvre is on port side, (6 × 160) + 500 = 1460 m and on starboard side, 0.3 nm (555.6 m) + (6 × 160) + 500 = 2015.6 m. However, 1 nm (1852 m) is recommended by the port traffic control for vessels moving in a line, under same speed forward, and with similar headings (Hsu, 2014). So, the remaining distance before the minimum safe distance starts is 3000 – 1852 =1148 m. The proposed collision alert system will use the hull sensor to check the safe distance frequently and hence alert the shipmaster in real-time. If the total distance between vessels, D = 3000 m and safe distance for vessels moving in a line, under same speed forward, and with similar headings, d_{safe} = 1852 m then remaining distance, d_{min} = 1148 m. It can be expressed as, $D = d_{\text{min}} + d_{\text{safe}}$. The remaining distance, d_{min} can be divided in four parts as, $x_1 = \frac{1}{4} d_{\text{min}}$, $x_2 = \frac{1}{2} d_{\text{min}}$, $x_3 = \frac{3}{4} d_{\text{min}}$ and $x_4 = d_{\text{min}}$.

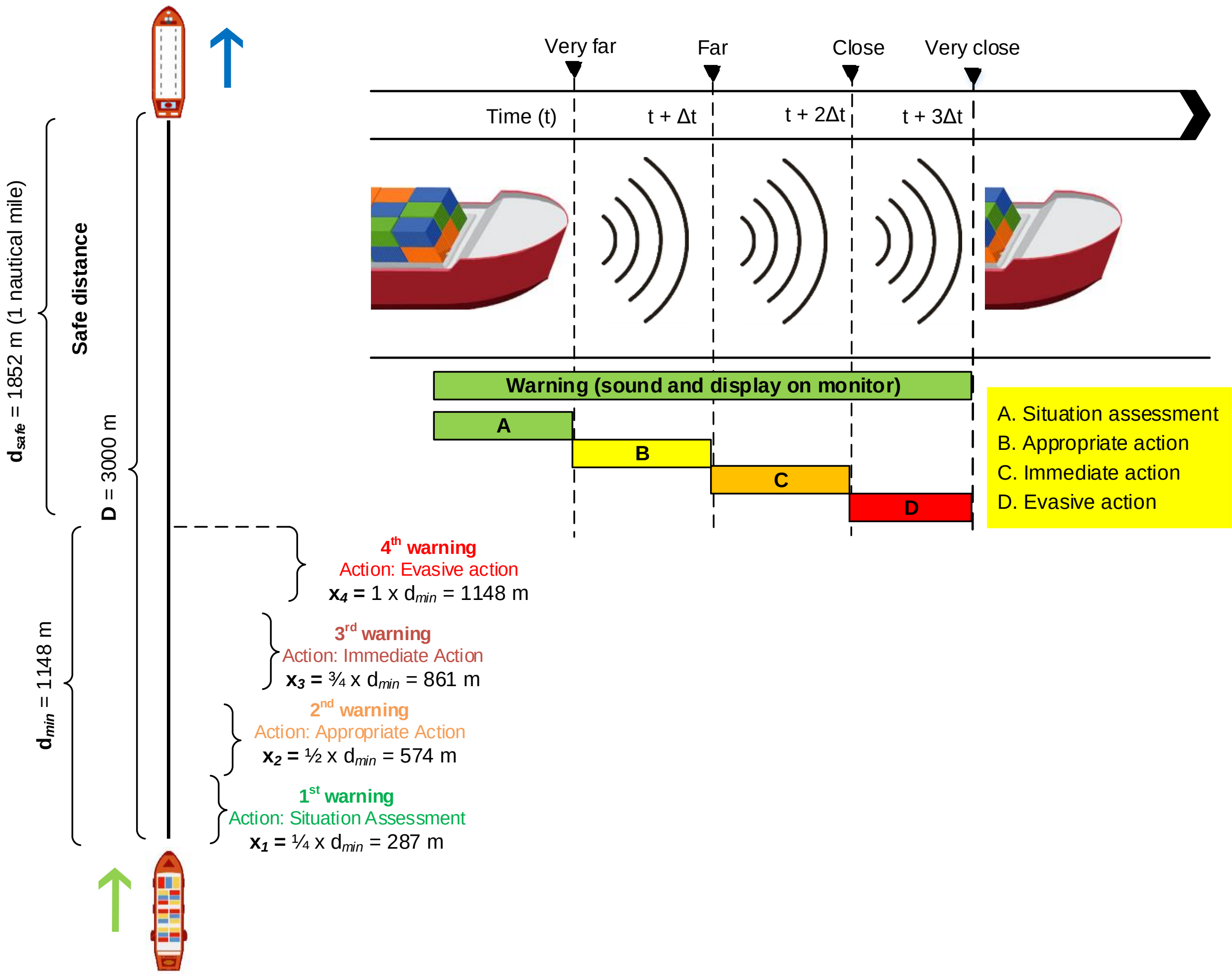

Figure 4–9: The distance between vessels in the port area moving in the same direction under same speed.

The “Warning” node has five states, (i) first alarm, (ii) second alarm, (iii) third alarm, (iv) final alarm, and (v) no alarm. It is assumed that the host vessel is approaching at medium speed with reasonable manoeuvrability. The likelihood of first alarm is increased when the host vessel embraces one-fourth of $d_{\min}$ which is considered as very far. The second alarm is activated when the vessel crosses half of $d_{\min}$ which distance is considered as far, and the third alarm is activated when vessel crosses one-third of $d_{\min}$ which is considered as close. The final alarm is activated when vessel crosses $d_{\min}$ which is considered as very close and requires evasive action. No alarm is kept as an option, when the risk is extremely low. The shipmaster is therefore being notified through the different states of the alarm to keep the minimum safe distance on the port, starboard and bow side.

The four “Decision making” nodes are dependent on “Warning”, and Decision-making skills (GSR, MTR, TKR, ESR and SER). In an emergency, the decision of a shipmaster is critical. The “Warning” node is dependent on “Navigational state”, “Weather and environment state”, “Own vessel speed”, “Target vessel distance”, and “Own vessel manoeuvrability”. The “Own vessel manoeuvrability” node is dependent on “Target vessel type”, “Target vessel length (m)”, and “Target vessel speed”. The input node “Target vessel distance” has four states: very far, far, close and very close. Similarly, “Own vessel speed” and “Target vessel speed” have three states: low, medium and high. “Target vessel type” has four states: cargo, tanker, passenger and fishing and “Own vessel manoeuvrability” has three states as reasonable, tight and extremely tight. The outputs of preceding OOBNs (e.g., human factor state, navigational and manoeuvring state, visibility state and environment state), as well as other nodes (e.g., own vessel speed, target vessel distance, and own vessel manoeuvrability), are taken into consideration in the proposed model (Figure 4–10).

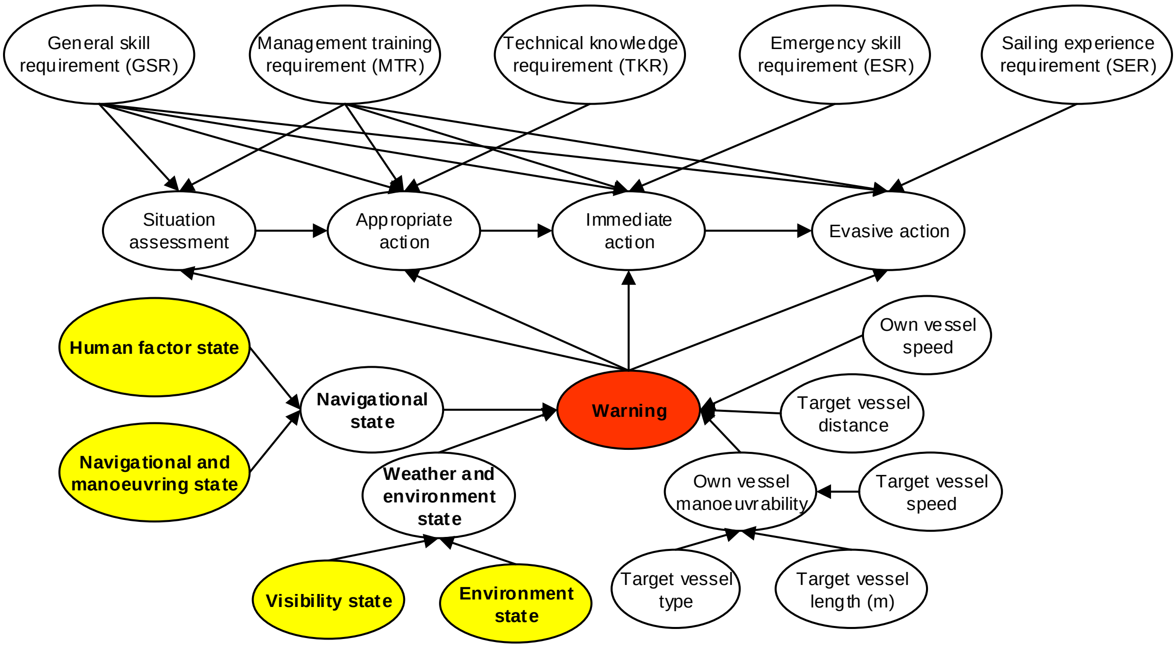

Figure 4–10: OOBN model for the confined area.

The model in Figure 4–10 explicitly combines all the preceding OOBNs to form a larger model for collision alert and decision making at a different stage of vessel navigation from a very far distance to very close distance.

4.3.9. OOBN model update

The proposed method takes advantage of case scenario data and updating mechanisms to reassess the risk regarding new information. In Bayesian updating approach, new information is employed in the form of likelihood functions to update prior probabilities using Bayes' theorem (Kanes et al., 2017; Kelly, 2011; Meel and Seider, 2006). Although the time slice is not considered in the proposed model, the observations (e.g., new evidence) however, can be a function of time. In Figure 4–10, all the individual OOBNs and the individual linked nodes are illustrated. The prior probabilities in the OOBNs, as well as in the individual nodes, are updated continuously as new information becomes available, as illustrated in Figure 4–10. The internal nodes "Human factor state", "Navigational and manoeuvring state", "Visibility state", and "Environment state" are kept encapsulated. In these encapsulated nodes, any new nodes can be added, or existing nodes can be subtracted without affecting the entire network. The "Decision" node will update itself when the prior probability is updated in the model. The complete BN for the MCAR system is illustrated in Figure 4–11.

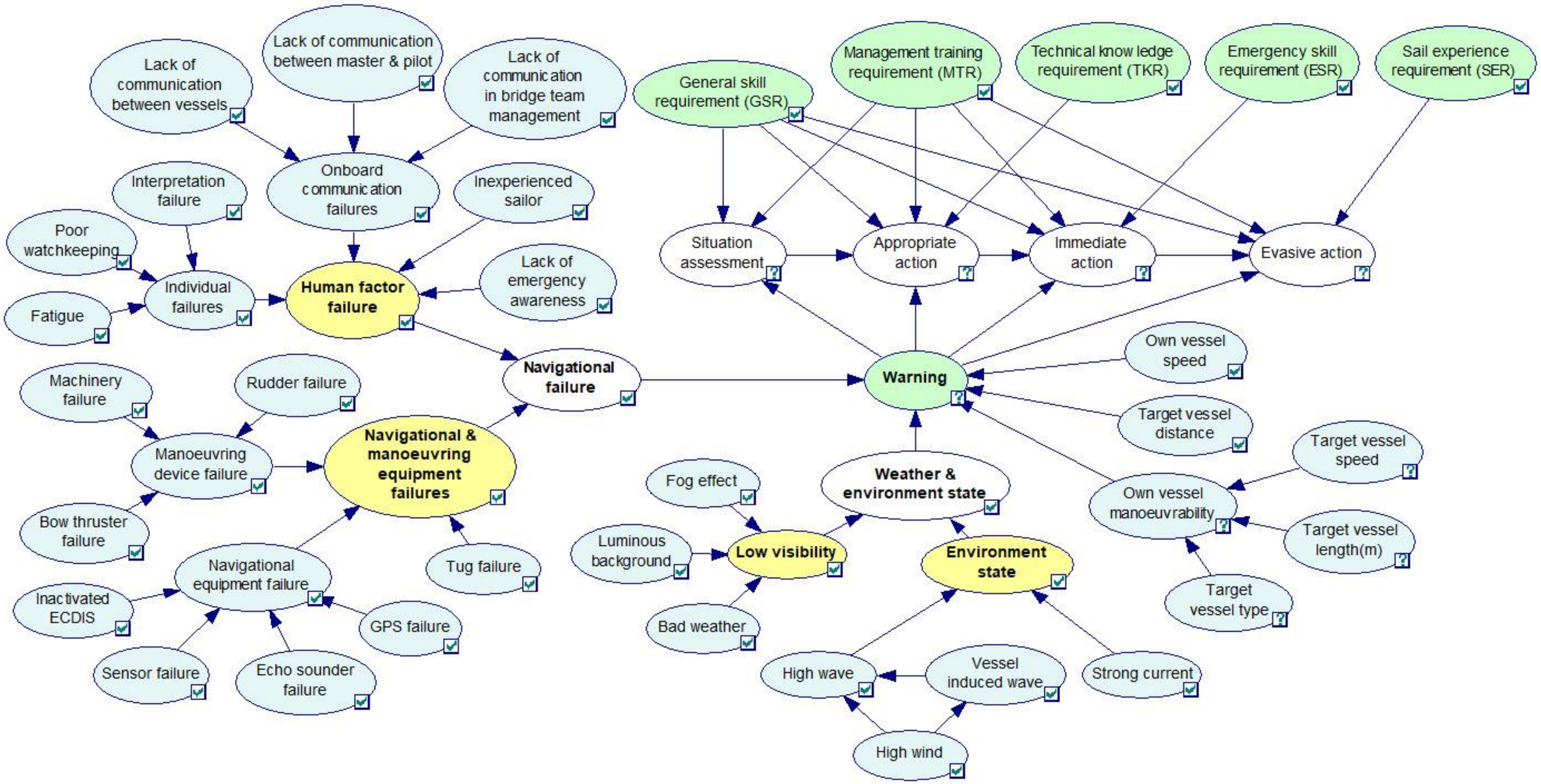

Figure 4–11: The complete MCAR model for the confined area.

4.4. Application of the collision alert model: case studies

The application of the proposed method is applied in two generic case studies, (i) a bulk carrier navigating through Malacca-Singapore Straits, and (ii) a cargo ship navigating the north-western coast of Oo Shima towards Takuma port. The detailed scenarios are analysed using the OOBN as shown in Figure 4–11 which is the complete version of Figure 4–10. The prior probabilities are assigned based on literature reviews and expert judgment. In the following sections, the application of the proposed methodology is applied to a case study of a large vessel navigating through the confined area.

4.4.1. Case study 1: Bulk carrier navigating through Singapore-Malacca Straits

The Straits of Malacca and Singapore are considered to be a major gateway for trade between the Far East, the oil-rich states in the Middle East and ports along the way (Qu and Meng, 2012). An estimated 200 vessels pass through the straits on a daily basis, carrying almost 80% of the oil transported to Northeast Asia (Gilmartin, 2008). The high-volume traffic coupled with the narrow passage makes the Straits challenging for mariners. The Straits are about 2.8 km wide along with 2.1 km long shipping waterways at Phillips Channel (Qu and Meng, 2012). The region experiences frequent rain, windstorms and fog and, strong currents can be experienced during the transit through the Straits (StrasseLink, 2014). Low visibility due to fog makes it difficult for mariners to navigate through the Straits. Human error, such as fatigue and intense stress, also contributes to navigational hazards in the Straits (Zaman et al., 2015). The Joint War Committee (JWC) of Lloyd’s Market Association (LMA) declared the Straits of Malacca and Singapore to be on the list of high-risk areas in June 2005 (Wu and Zou, 2009). The geographical view of Straits of Malacca and Singapore, adopted from SAFETY4SEA (2014), is illustrated in Figure 4–12.

Figure 4–12: Geographical view of the Straits of Malacca and Singapore.

In this case study, a bulk carrier is assumed to navigate through Singapore-Malacca Straits. It follows a route from the South China Sea to Singapore Strait then Malacca Strait to the Indian Ocean. However, a large oil tanker (222 m long) is sailing in the same direction preceding the bulk carrier. In this study, the bulk carrier is assumed to proceed with medium speed, and the distance between the vessels is about 1.5 nautical miles. It is almost the end of summer and some early storms result in low visibility in the Straits. The bulk carrier's shipmaster is fully aware of the situation, and there are no mechanical issues so far on the vessel. The oil tanker is passing through the narrow Phillips Channel at 05:30 hours and experiencing some unsteadiness due to strong current, and low visibility is affecting normal operation. Due to low visibility, the bridge master on the bulk carrier failed to locate the oil tanker. However, a first warning is shown on the dashboard when the bulk carrier passed one-fourth of the minimum distance before the safe distance starts. The shipmaster ignored the warning as no indication was given from the bridge. As soon as the bulk carrier entered the narrow Phillips Channel, the crew heard one long blast on a horn. The bulk carrier was too close to alter course and collided on the starboard side of the oil tanker at 06:15 hours.

Based on the above scenario, the probability assessment scenario was carried out using four different times in the selected area, as shown in Figure 4–13. In this case, the scenarios have been taken at local times 05:15, 05:30, 05:45 and 06:00 hours. Response for each risk factor associated with bulk carrier navigation in the Singapore-Malacca Straits is recorded and demonstrated in Table 4-6. The BN simulation of the model is shown in Figure 4–14. The result of the probability assessment is classified in Table 4-7.

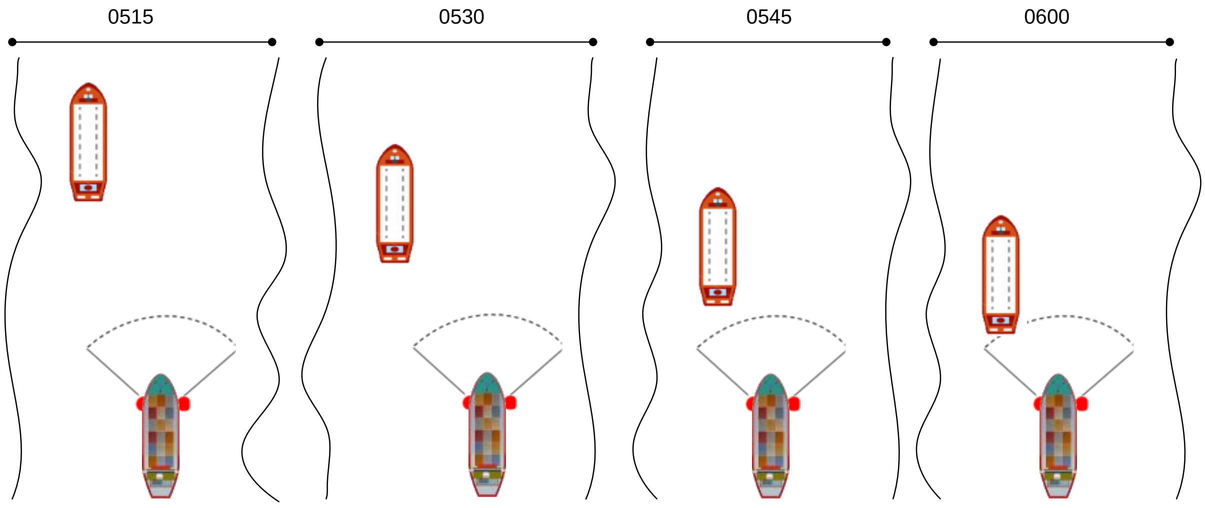

Figure 4–13: Forward collision in the Phillips Channel.

Table 4-6: Response to risk factors associated with bulk carrier navigation in Singapore-Malacca Straits.

OOBN classes	Risk factors	Time, 0515 hrs	Time, 0530 hrs	Time, 0545 hrs	Time, 0600 hrs
Human factor state	Interpretation failure	*no*	*no*	*no*	*no*
	Fatigue	*no*	*no*	*no*	*no*
	Poor watchkeeping	*yes*	*yes*	*yes*	*yes*
	Lack of communication between vessels	*no*	*no*	*no*	*no*
	Lack of communication between master and pilot	*no*	*no*	*no*	*no*
	Lack of communication in bridge team management	*no*	*no*	*no*	*no*
	Lack of emergency awareness	*no*	*no*	*no*	*no*
	Inexperienced sailor	*no*	*no*	*no*	*no*
Navigational and manoeuvring equipment state	Rudder failure	*no*	*no*	*no*	*no*
	Machinery failure	*no*	*no*	*no*	*no*
	Bow thruster failure	*no*	*no*	*no*	*no*
	Inactivated ECDIS	*no*	*no*	*no*	*no*
	Sensor failure	*no*	*no*	*no*	*no*
	Echo sounder failure	*no*	*no*	*no*	*no*
	GPS failure	*no*	*no*	*no*	*no*
	Tug failure	*no*	*no*	*no*	*no*
Low visibility state	Fog effect	*yes*	*yes*	*yes*	*yes*
	Bad weather	*yes*	*yes*	*yes*	*yes*
	Luminous background	*no*	*no*	*no*	*no*
Environment state	High wind	*no*	*no*	*no*	*no*
	Strong current	*yes*	*yes*	*yes*	*yes*
	Own vessel speed	*medium*	*medium*	*medium*	*medium*
	Target vessel distance	*very far*	*far*	*close*	*very close*
	Target vessel speed	*medium*	*medium*	*medium*	*medium*

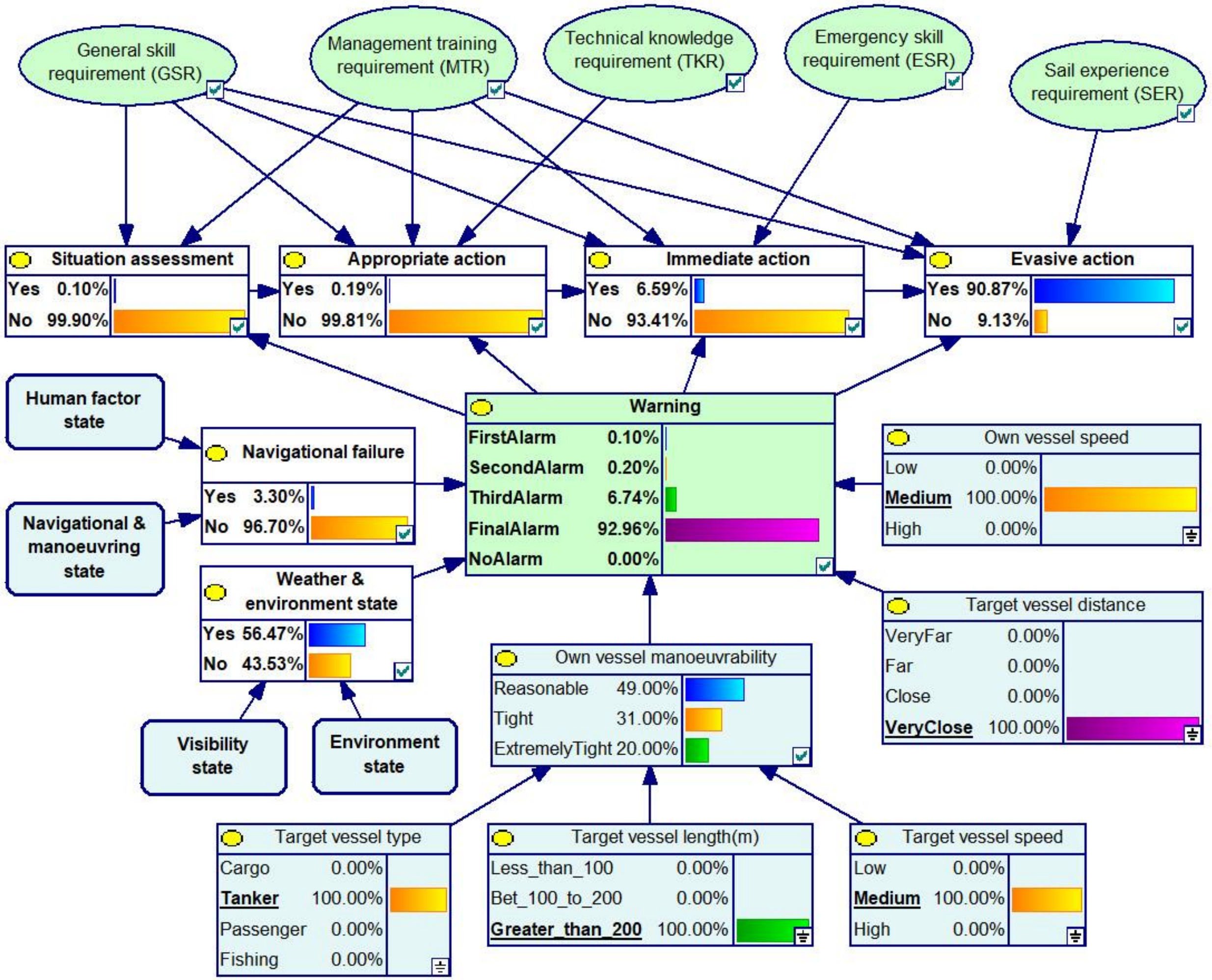

Figure 4–14: BN simulation results of bulk carrier navigating through Malacca-Singapore Straits at 0600 hours.

Table 4-7: Model outcome based on available information on the four-time step (case study 1).

	Time (hours)			
	0515	0530	0545	0600
	Bulk carrier			
	D: *Very far* S: *Medium*	D: *Far* S: *Medium*	D: *Close* S: *Medium*	D: *Very close* S: *Medium*
1st warning (%)	92.96	7.04	0.10	0.10
2nd warning (%)	0.00	92.96	6.94	0.20
3rd warning (%)	0.00	0.00	92.96	6.74
4th warning (%)	0.00	0.00	0.00	92.96
No warning (%)	7.04	0.00	0.00	0.00
Situation assessment (%)	92.81	7.02	0.10	0.10
Appropriate action (%)	0.43	89.78	6.70	0.19
Immediate action (%)	2.08	0.46	90.89	6.59
Evasive action (%)	2.17	2.36	1.45	90.87

*D – Distance (Target vessel), S – Speed (Own vessel)

Based on the model outcome shown in Table 4-7, the first warning is given around 05:15 local time for situation assessment when the distance was very far between two vessels. However, no assessment is done to locate any surrounding vessels or environmental obstacles but rather the same speed has been maintained which has resulted in the second warning at 05:30 hours. Again, appropriate action is not taken (e.g., lack of technical knowledge) and hence, the third warning is activated at 05:45 which requires immediate action. At 05:30, the course and the speed of the oil tanker deviated against a strong current in low visibility as it passes through the narrow Straits. The shipmaster of the bulk carrier failed to take immediate action such as manoeuvring and controlling the astern propulsion which has resulted in a final warning. At 06:00 hrs the oil tanker has almost passed through the Straits as well as the harsh environment. However, the bulk carrier passed the safe distance domain and failed to manoeuvre due to close distance, and as a result, collision occurred. Table 4-7 shows a clear-view of the risk level, and as the level of risk increases the probability of warning level also increases. Similarly, lower risk decreases as the situation crosses that threshold.

4.4.2. Case study 2: Collision scenario between a cargo ship and a recreational fishing vessel

In this section, a collision scenario between a cargo ship and a recreational fishing vessel is studied to demonstrate the application of the proposed MCAR collision alert model. This case study is adopted from the Japan Transport Safety Board (JTSB) website (JTSB, 2011). The characteristics of port areas differ and are unique when compared to open waters. Therefore, particular factors such as wind and wave effect, current effect, safe distance, and any mechanical issues might have a significant influence on the risk associated with vessel's navigation in the port areas. Estimated vessel tracking from Keihin port to Takuma port is illustrated in Figure 4–15.

A cargo vessel (vessel A) departed from Keihin port around 07:00 hrs local time and is heading toward Takuma port (south-westward). The vessel is sailing at a speed of approximately 11.5 knots under hazy conditions with a number of recreational fishing vessels spotted in the area. Two radars and GPS have confirmed vessel location. The master of the cargo vessel is engaged in organising the vessel's chart as no vessels are visible by way of visual lookout. From the bridge, the chief cargo engineer notices the mast of a fishing vessel (vessel B, 45 m in length) moving in the bow direction, and then turns and immediately informs the cargo vessel master. At the same time, a passenger seated on the port side of the aft section of the fishing vessel informs the skipper about the cargo vessel. The skipper looks in the bow direction and notices the cargo vessel approaching approximately 45º ahead to port, and immediately engages the engine to full astern. The master of the cargo vessel immediately engages the clutch to astern as soon as the fishing vessel becomes visible. Around 1100 hrs, the bow of the cargo vessel sways the starboard side of the fishing vessel. During the incident, the weather was cloudy and hazy with light and dark areas (low visibility 2-5 m). The ocean current and tide were moving at a speed of approximately 0.5 – 1.2 knots from north-eastward to eastward.

Figure 4–15: Estimated vessel track heading towards Takuma post from Keihin port.

Based on the information provided in the scenario, the collision scenario was carried out using four different times in the selected area, as shown in Figure 4–16. In this case, the scenarios are taken at local times 10:15, 10:30, 10:45 and 11:00 hours. Response for each risk factor associated with the cargo carrier navigating the north-western coast of Oo Shima is recorded and demonstrated in Table 4-8. The BN simulation of the developed model is shown in Figure 4–17. The result of the probability assessment is shown in Table 4-9.

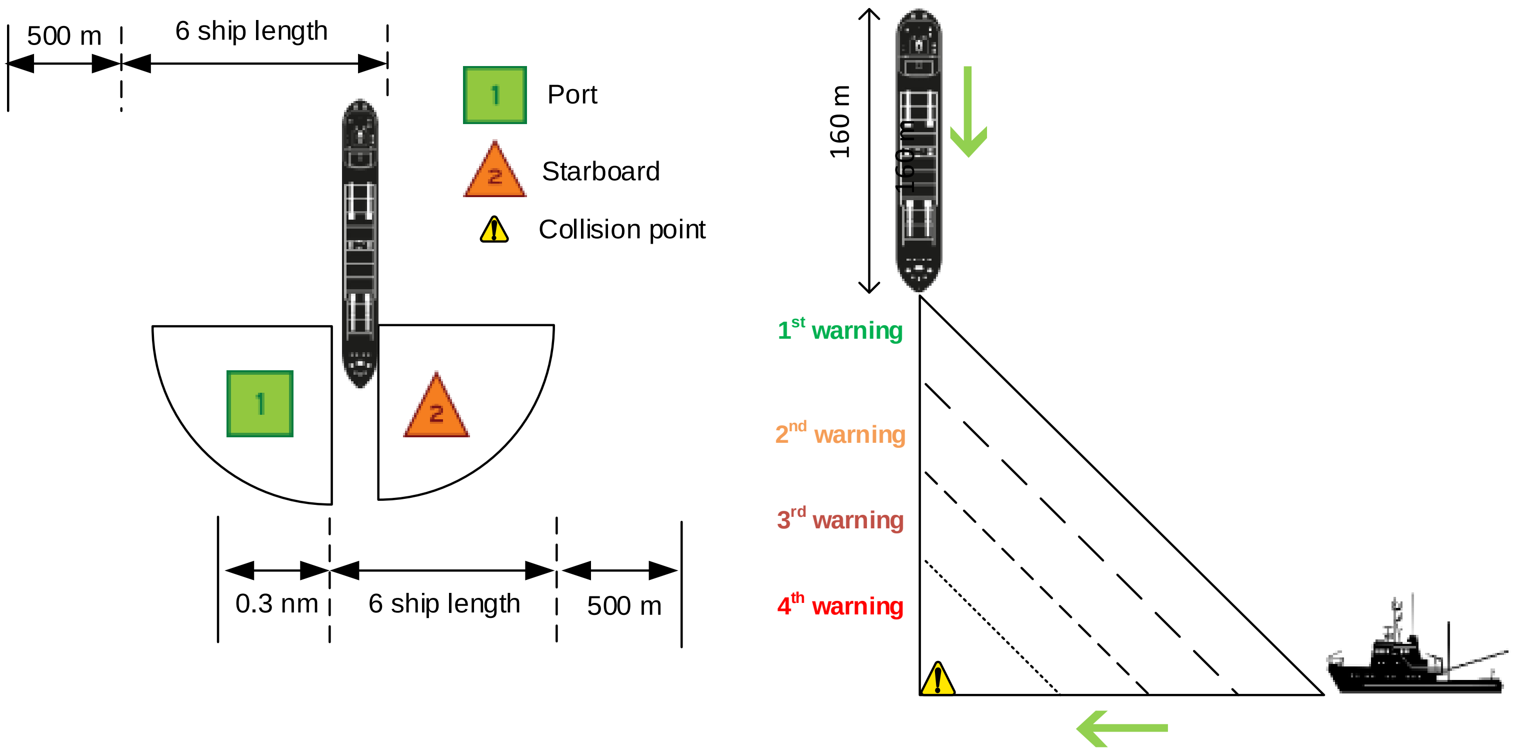

Figure 4–16: Forward collision between cargo and fishing vessel on the north-western coast of Oo Shima.

Table 4-8: Response to risk factors associated with cargo ship navigation near Oo Shima.

OOBN classes	Risk factors	Time, 1015 hrs	Time, 1030 hrs	Time, 1045 hrs	Time, 1100 hrs
Human factor state	Interpretation failure	*no*	*no*	*no*	*no*
	Fatigue	*no*	*no*	*no*	*no*
	Poor watchkeeping	*yes*	*yes*	*yes*	*yes*
	Lack of communication between vessels	*no*	*no*	*yes*	*yes*
	Lack of communication between master and pilot	*yes*	*yes*	*yes*	*yes*
	Lack of communication in bridge team management	*yes*	*yes*	*yes*	*yes*
	Lack of emergency awareness	*yes*	*yes*	*yes*	*yes*
	Inexperienced sailor	*yes*	*yes*	*yes*	*yes*
Navigational and manoeuvring equipment state	Rudder failure	*no*	*no*	*no*	*no*
	Machinery failure	*no*	*no*	*no*	*no*
	Bow thruster failure	*no*	*no*	*no*	*no*
	Inactivated ECDIS	*no*	*no*	*no*	*no*
	Sensor failure	*no*	*no*	*no*	*no*
	Echo sounder failure	*no*	*no*	*no*	*no*
	GPS failure	*no*	*no*	*no*	*no*
	Tug failure	*no*	*no*	*no*	*no*
Low visibility state	Fog effect	*yes*	*yes*	*yes*	*yes*
	Bad weather	*yes*	*yes*	*yes*	*yes*
	Luminous background	*no*	*no*	*no*	*no*
Environment state	High wind	*no*	*no*	*no*	*no*
	Strong current	*yes*	*yes*	*yes*	*yes*
	Own vessel speed	*medium*	*medium*	*medium*	*medium*
	Target vessel distance	*very far*	*far*	*close*	*very close*
	Target vessel speed	*medium*	*medium*	*medium*	*medium*

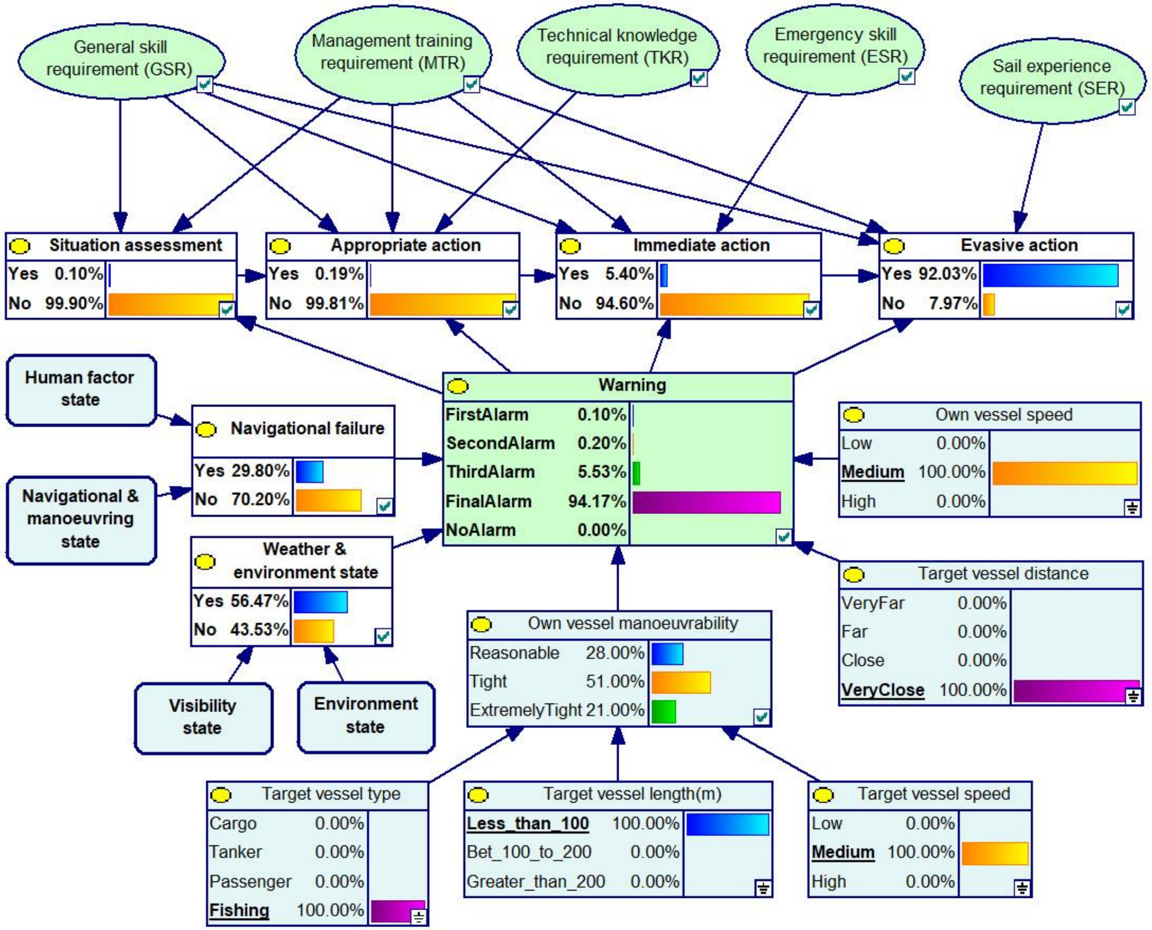

Figure 4–17: BN simulation results of a cargo ship navigating the north-western coast of Oo Shima at 1100 hours.

Table 4-9: Model outcome based on available information on the four-time step (case study 2).

	Time (hours)			
	1015	1030	1045	1100
	Cargo carrier			
	D: *Very far* S: *Medium*	D: *Far* S: *Medium*	D: *Close* S: *Medium*	D: *Very close* S: *Medium*
1st warning (%)	94.17	5.83	0.10	0.10
2nd warning (%)	0.00	94.17	5.73	0.20
3rd warning (%)	0.00	0.00	94.17	5.53
4th warning (%)	0.00	0.00	0.00	94.17
No warning (%)	5.83	0.00	0.00	0.00
Situation assessment (%)	94.02	5.82	0.10	0.10
Appropriate action (%)	0.43	90.95	5.53	0.19
Immediate action (%)	2.11	0.43	92.07	5.40
Evasive action (%)	2.20	2.36	1.44	92.03

*D – Distance (Target vessel), S – Speed (Own vessel)

Based on the model outcome shown in Table 4-9, the first warning was given around 10:15 local time for situation assessment when the angle distance was very far between two vessels. The master of the cargo carrier was relying on visual operation rather than using radar or other devices whilst organising the vessel chart. No assessment was done after the first warning to understand the situation of surrounding vessels to ensure safety. This resulted in a second warning at 10:30 hours. Due to lack of technical knowledge and skills, appropriate action was not taken and hence, the third warning, which required immediate action, was activated at 10:45. Due to lack of emergency skills and low visibility, the master of the cargo carrier failed to take immediate action such as manoeuvring immediately and control astern propulsion which resulted in a final warning. At 11:00 hrs the cargo carrier passed safe distance domain and failed to manoeuvre due to close distance. As a result, the collision occurred, and significant damage was done to the fishing vessel. Table 4-9 shows the increasing level of risk as the probability of warning level increases and the lower risk decreases as the situation crosses that threshold.

The above analysis reveals that the proposed OOBN methodology allows estimation of the different level of risk during navigation in a confined area or narrow channel under certain conditions. Different environmental and operational conditions as well as human factors that can affect the navigation, are identified and considered as primary causes. By applying prior probabilities to these primary causes or risk factors in the developed model, it is plausible to determine the level of risk and act accordingly. Each subclass can be integrated into a single network to see the possible outcome. An additional risk factor can be added or subtracted from each subclass without modifying the entire network which is considered to be an advantage of the OOBN.

4.5. Conclusion

A conceptual model, MCAR, based on OOBN methodology is proposed to estimate the level of risk and real-time decision making under certain conditions in the presence of stationary and non-stationary objects in a narrow channel and confined area. By taking advantage of the OOBN, a large network was encapsulated with different subclasses that could be easily modified without affecting the entire network. It can be useful to identify the root cause of each subclass and analyse each individually. The applicability of the proposed methodology has been demonstrated through two case scenarios in a confined area or narrow channel; a bulk carrier navigating through Malacca-Singapore Straits, and a cargo ship navigating the north-western coast of Oo Shima. This model estimates the level of risk by taking into consideration vessel kinematics, different operational and environmental factors as well as human factors in a confined area and provides early warning. Five decision-making skills such as general skill, management training, technical knowledge, emergency skill and sailing experience are employed as a requirement in an emergency. The probability obtained through the proposed methodology can be used to make a real-time decision, such as situation assessment, appropriate and immediate action, followed by evasive action. The simulated result shows the increasing level of risk as the probability of warning level increases. Similarly, lower risk decreases as the situation crosses that threshold. The developed methodology can be used in a confined area or narrow channel to investigate the possibility of preventing and mitigating vessel collision to stationary or non-stationary objects.

Acknowledgements

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Chapter 5: Conclusions, Recommendations and Further Work

This chapter presents the main conclusions of this research and a number of recommendations for further work.

5.1. Conclusions

The aim of this thesis is to develop an advanced probabilistic model for accident modelling in marine and offshore operations. In chapters 2 and 3, the model development is focused on Bayesian Network (BN). In the last section of the study, Object-Oriented Bayesian Network (OOBN) is utilised to model and integrate a distinct subclass. OOBN framework is selected due to its capability to control encapsulated subnetworks for individual analysis of root causes, and addition/subtraction of new nodes without modifying the entire network. Each specific task has been included in each chapter with details.

On the basis of the reported findings in this thesis, the following main conclusions can be drawn:

- A review of existing scenario-based modelling approaches reveals ignoring evolving scenarios in modelling of accident scenarios. Hence, a network based model is developed to envisage the most probable accident scenarios in complex offshore process facilities. By using BN, conditional dependency has been illustrated between the primary causes and the consequences through direct causal arcs. The posterior likelihood of consequences has been estimated using prior data. In addition, the prior probability has been updated considering the evidence of specific consequences. The application of the proposed model has been demonstrated on two specific case studies, viz. ammonia and LNG release on process facility. Five different accident scenarios are shortlisted for the ammonia release study. Consequences such as toxic release, Boiling Liquid Expanding Vapour Explosion (BLEVE) and vapour cloud explosion (VCE) were identified. For the LNG release study, four different accident scenarios are shortlisted. Fire and explosion consequences such as pool fire, jet fire and VCE were identified. Using the Maximum Credible Accident Scenarios (MCAS) method, damages such as fatalities, financial and the environmental loss as are estimated for above scenarios as well as the credible values for individual fire and explosion and toxic release consequences. For the ammonia release study, the final credible value of BLEVE has been estimated to 0.47 in terms of fire and explosion. For the toxic release event, the final credible value of toxic release event has been estimated to 1.0, 1.0, 0.86, 0.01 and 0.61 respectively. A higher fatalities and environmental loss are observed due to a toxic release in scenario 1 and 2. However, a higher degree of financial loss is also observed in scenario 3 due to a BLEVE. In terms of fire and explosion, scenario 3 is the most credible. In terms of toxic release, scenario 1, 2 and 3 are the most credible. Overall, scenario 3 is the most credible in terms of combined effect of fire and explosion and toxic release. For the LNG release study, the final credible value of pool fire, VCE and jet fire has been estimated to 0.31, 0.63 and 0.14 respectively. Due to instantaneous release of LNG in scenario 2, higher degree of financial loss and fatalities are observed for VCE. Hence, scenario 2 is the most credible in terms of fire and explosion. For the ammonia release study, the high pressure and sudden expansion inside the vessel had the most effect on BLEVE in terms of scenario 3. In scenario 1, 2 and 5, a pressurised release of ammonia gives rise to a two-phase discharge which may result in toxic effect in absence of ignition source. For the LNG release study, the unpressurised condition had more effect on pool fire in comparison to the VCE and jet fire. In terms of liquid release, VCE and jet fire is more influenced. However, in terms of dispersion, dense cloud has more effect on VCE. The developed concept model can be applicable to the other offshore process facilities.

- The existing transportation accident models consider individual events and independent causation factors that may particularly lead to the accidents on the NSR. This study focuses on developing a dynamic risk-based model to analyse shipping accidents in the Arctic waters. Application of the developed methodology is reliant on Bayesian Network modelling and takes the advantages of case-specific data and updating mechanisms to reassess the risk. In the developed model, ship collisions with ice during navigation in Arctic routes were considered. However, accident scenarios, such as foundering, and grounding were also considered due to the likelihood of their taking place. The risk analysis revealed that the East Siberian Sea had the highest probabilities regarding collision, foundering and grounding of the ship. Other regions such as Chukchi, Laptev, Kara and the Barents Sea have almost similar probabilities regarding grounding. However, foundering probabilities are very low in all five areas. The sensitivity analysis of collision, foundering and grounding events also revealed that the developed model was sensitive to several environmental and operational conditions. From the BN and subsequent sensitivity analysis, it is clear that some of the root nodes are the dominant factors towards the accidental event. This contribution is the highest for collision and foundering where an increase of the initial probability leads to a significant change in the probability of the occurrence of accidental events. In the cases of grounding, this effect is less significant. The developed approach can be helpful for decision makers and safety experts to estimate the probability of different types of marine ship accidents considering the factors most contributing to the existing environmental and operational conditions. The developed methodology can be used to investigate the possibility of preventing and mitigating ship accidents in harsh and cold environments.

- A conceptual model, MCAR, based on OOBN methodology is proposed to estimate the level of risk and real-time decision making under certain conditions in the presence of stationary and non-stationary objects in a narrow channel and confined area. By taking advantage of the OOBN, a large network was encapsulated with different subclasses that could be easily modified without affecting the entire network. It can be useful to identify the root cause of each subclass and analyse each individually. The applicability of the proposed methodology has been demonstrated through two case scenarios in a confined area or narrow channel; a bulk carrier navigating through Malacca-Singapore Straits, and a cargo ship navigating the north-western coast of Oo Shima. This model estimates the level of risk by taking into consideration vessel kinematics, different operational and environmental factors as well as human factors in a confined area and provides early warning. Five decision-making skills such as general skill, management training, technical knowledge, emergency skill and sailing experience are employed as a requirement in an emergency. The probability obtained through the proposed methodology can be used to make a real-time decision, such as situation assessment, appropriate and immediate action, followed by evasive action. The simulated result shows the increasing level of risk as the probability of warning level increases. Similarly, lower risk decreases as the situation crosses that threshold. The developed methodology can be used in a confined area or narrow channel to investigate the possibility of preventing and mitigating vessel collision to stationary or non-stationary objects.

5.2. Recommendations and Further Work

There are several improvements that can be implemented in future work. I propose the following points for future research:

- **Uncertainty analysis:** Uncertainty assessment needs to be considered in the developed models. There are various uncertainties associated with the models and the considered factors. Considering these uncertainties within the model will increase the confidence and accuracy of the final results received in accident modelling and consequence analysis.

- **Proximity sensor:** Use of proximity sensor in collision avoidance system has been available in the auto industry for a long time. The marine industry can also use similar close proximity sensor on ships and boats during navigation which can be useful for crew members.

- **Head-up display:** Most of the modern auto vehicles in autonomous/non-autonomous category have quickly adopted head-up display features as has the aviation industry. Marine vessels can also be equipped with head up display, and facilitate the most up to date features.

- **Expert elicitation:** Expert elicitation plays an important role in BN construction, quantification and validation. We can use their expertise and reuse previously elicited information which would be a valuable contribution to the BN modelling.

- **Other approaches:** The Bayesian Network framework developed in this thesis can be compared to other probabilistic tools and machine learning algorithms. It would be interesting and beneficial to investigate the new technique.

- **Operating condition:** The operating condition in harsh environment needs to be studied. Cold operating environment are often supported with very limited navigational support during ship operation. Ship operations in ice and severe sub-zero temperatures may expose ship operators and crews to unique risks and considerations. Hence, IMO regulations, procedures and recommendations for ships operating in cold and harsh environments need to ensue.

- **Study of natural hazards:** Natural hazards such as earthquakes, tsunamis, cyclones and storms/wave surges are naturally occurring physical phenomena which are caused either by rapid or slow onset events. It is therefore important to study the impact of such natural hazards.

Appendix A

An application of BN to envisage potential accidents in FLNG facility

This conference paper was presented at the 12th International Offshore and Polar Engineering (ISOPE) Pacific/Asia Offshore Mechanics Symposium (PACOMS-2016) in Gold Coast, Brisbane, Australia. The citation for this paper is:

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